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TECHNOLOGY ADVANCEMENT OF THE ELECTROCHEMICAL CO_2 CONCENTRATING PROCESS

ANNUAL REPORT

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F.H. Schubert, R.R. Woods,
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Prepared Under Contract NAS2-8666

by

Life Systems, Inc.
Cleveland, OH 44122

for

AMES RESEARCH CENTER
National Aeronautics and Space Administration

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FOREWORD

The development work described herein was conducted by Life Systems, Inc. at Cleveland, Ohio under Contract NAS2-8666, during the period of March, 1977 through January, 1978. All program activities are scheduled for completion by May, 1979. The Program Manager is Franz H. Schubert. The personnel contributing to the program and their responsibilities are outlined below:

Personnel	Area of Responsibility
Steve Czernec	Mechanical Component/System Assembly and Checkout
Tim M. Hallick	Program Testing, Data Reduction, Module/Cell Configurations
Dennis B. Heppner, PhD	Component Design, Laboratory Breadboard Testing, System Integration
Don W. Johnson	Electronic Assembly and Checkout
Lynn W. Krebs	Software Module Design
Richard D. Marshall	System Integration, Electrochemical Design, Optimum Current Density Study
J. David Powell	Control and Monitor Instrumentation and Sensor Design
Franz H. Schubert	Program Manager, System Analysis and Design
John W. Shumar	Product Assurance, Electrode/Matrix Development
Daniel C. Walter	Mechanical Component and System Packaging
Richard R. Woods, Jr.	Supporting Technology Studies, Electrochemical and Chemical Performance Analysis
Rick A. Wynveen, PhD	Program Administration, Electrochemical Support, Concept Evaluations
Jim Y. Yeh, PhD	Control and Monitor Instrumentation Software

The contract's Technical Monitor is P. D. Quattrone, Chief, Advanced Life Support Project Office, NASA Ames Research Center, Moffett Field, CA.

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LIST OF ACRONYMS

ACS	Attitude Control System
AEDC	Advanced Electrochemical Depolarized CO_2 Concentrator
ARS	Air Revitalization System
ARX-1	One-Person Experimental Air Revitalization System
ASU	Air Supply Unit
B-CRS	Bosch CO_2 Reduction Subsystem
CHCS	Cabin Humidity Control Subsystem
C/M I	Control/Monitor Instrumentation
CRS	CO_2 Reduction Subsystem
CRT	Cathode Ray Tube
CS-6	Six-Person, SSP CO_2 Concentrator Subsystem
EC/LSS	Environmental Control/Life Support System
EDC	Electrochemical Depolarized CO_2 Concentrator
EDCM	EDC Module
NSS	Nitrogen Supply Subsystem
OGS	Oxygen Generation Subsystem
ORS	Oxygen Recovery System
S-CRS	Sabatier CO_2 Reduction Subsystem
SSP	Space Station Prototype
TSA	Test Support Accessories
WHS	Water Handling Subsystem

SUMMARY

Regenerative carbon dioxide removal concepts are needed to sustain man in space for extended periods of time. A program to develop an Electrochemical Carbon Dioxide Concentration technique has been underway at the National Aeronautics and Space Administration and Life Systems, Inc. for the past several years. The work reported herein, "Technology Advancement of the Electrochemical Carbon Dioxide Concentration Process," is a portion of the overall program.

During the present reporting period, activities in four major areas were successfully completed:

1. Development of subsystem hardware and concepts for integration into a one-person, experimental Air Revitalization System based on the advanced, liquid-cooled Electrochemical Depolarized Carbon Dioxide Concentrator.

2. Development of Test Support Accessories to support the system level testing of the one-person Air Revitalization System.

3. Testing of an air-cooled, four-person capacity, Electrochemical Depolarized Carbon Dioxide Concentrator integrated with a Bosch Carbon Dioxide Reduction Subsystem and an Oxygen Generation Subsystem to form a laboratory breadboard Oxygen Recovery System.

4. Technology advancement studies of the basic electrochemical carbon dioxide concentration process to improve carbon dioxide removal and electrical efficiencies over broad operating ranges and to provide a basis for the design of the next generation cell, module and subsystem hardware.

In prior testing a liquid-cooled Electrochemical Depolarized Carbon Dioxide Concentrator, a Sabatier-based Carbon Dioxide Reduction Subsystem and an Oxygen Generation Subsystem were successfully integrated at the subsystem level and operated as a one-person capacity laboratory breadboard Oxygen Recovery System. The next logical step in the development of the advanced, liquid-cooled, Electrochemical Depolarized Carbon Dioxide Concentrator was completed as part of this program by integrating the carbon dioxide removal function with other air revitalization functions to form a self-contained, one-person Air Revitalization System.

A six-cell, liquid-cooled, advanced Electrochemical Depolarized Carbon Dioxide Concentrator module was fabricated using the previously developed advanced, lightweight, cell frames. This six-cell module was designed to meet the carbon dioxide removal requirements of one person, i.e., 1.0 kg/d (2.2 lb/d). Cabin humidity control subsystem hardware supplying preconditioned air to the Electrochemical Carbon Dioxide Concentrator as well as controlling cabin humidity was designed and fabricated to be an integral part of the Electrochemical Depolarized Carbon Dioxide Concentrator Subsystem.

The combined carbon dioxide and water removal hardware was functionally integrated with other major Air Revitalization System components such as a Contractor-developed Sabatier Reactor, water handling and distribution hardware and liquid coolant loop components. Also, centralized Control and Monitor Instrumentation, including one-button startup and shutdown of the total integrated system, was designed and fabricated. An Oxygen Generation Subsystem and a Nitrogen Supply Subsystem being developed under other NASA Ames Research Center contracts will be integrated with the hardware developed under this program to complete the Air Revitalization System. Final integration checkout and testing of this experimental one-person Air Revitalization System will be performed during the next reporting period.

A substantial reduction in the total number of components, interconnections and subsystem interfaces was demonstrated by treating the required Air Revitalization System processes at the functionally integrated system level rather than as a series of individual subsystems that must be integrated. Also, generation of "real world" data (by testing in the projected final application configuration) as well as savings in testing costs and Test Support Accessories hardware are projected to be demonstrated during the program activities scheduled for the next reporting period.

Support of an integrated subsystem test program in the area of carbon dioxide removal was provided as part of the program activities. A four-person capacity, laboratory breadboard Oxygen Recovery System consisting of an air-cooled, Electrochemical Depolarized Carbon Dioxide Concentrator, a Bosch-based Carbon Dioxide Reduction Subsystem and a Static Water Feed Oxygen Generation Subsystem was successfully tested. A total of 900 hours of testing including checkout, shakedown, design verification and endurance testing was accomplished. Also included in this activity was testing of a previously developed cabin environmental simulator (Air Supply Unit). A 900 hour test of this device indicated that it is ready to support long-term testing of future subsystem hardware.

Test Support Accessories were designed and constructed to support the testing of the hardware integrated in the one-person Air Revitalization System. These Test Support Accessories included a Fluid Supply Unit, a Coolant Supply Unit, a vacuum source, electrical power sources, a parametric data display cabinet and the previously developed Air Supply Unit.

Supporting technology advancement studies were completed to support four specific areas relating to the electrochemical depolarized carbon dioxide concentrating process. These areas are: (1) development of a higher performance, lower cost alternate anode current collector design, (2) a study to determine the optimum current density of an Electrochemical Depolarized Carbon Dioxide Concentrator when used as an electrical power source as well as a carbon dioxide remover, (3) development of cell hardware configurations and concepts that enable the attainment of higher level performance goals (a cell voltage of 0.50 V and a carbon dioxide removal efficiency of 82% at a current density of 21.5 mA/cm^2 (20 ASF)) and (4) electrolyte mixture studies to enhance concentrator performance levels.

It is concluded from the results reported herein that an Electrochemical Depolarized Carbon Dioxide Concentrator is a viable solution for the removal of metabolically generated carbon dioxide aboard manned spacecraft. Continued development of related technology is recommended to further improve performance, decrease equivalent weight and increase hardware reliability. Successful completion of this development will produce timely technology necessary to plan future advanced environmental control and life support system programs and experiments.

INTRODUCTION

Regenerative processes for the revitalization of spacecraft atmospheres are essential in making long-term manned missions in space a reality.[1,2] An important step in this overall revitalization process is the collection and concentration of the metabolically produced carbon dioxide (CO_2) for oxygen (O_2) recovery.

The subject program continues the development and advancement of an electrochemical CO_2 concentrating process, a technique that allows for the continuous and efficient removal of CO_2 from a spacecraft's cabin atmosphere and delivering the CO_2 premixed with hydrogen (H_2) to a CO_2 Reduction Subsystem (CRS) for subsequent O_2 recovery.

Background

The Skylab program marked the beginning of the use of regenerative techniques for CO_2 collection using cyclic absorption/desorption beds containing commercial zeolites. The emerging requirement for maintaining the CO_2 content of a spacecraft's atmosphere at a CO_2 partial pressure (pCO_2) below 400 Pa (3 mm Hg) made the zeolite systems unattractive due to their resulting high weight and volume penalties.[3]

The electrochemical technique of concentrating CO_2 from an air environment has evolved over the past 12 years.[4-11] During this time the concept has progressed from single cell operation through the fabrication, testing and integration of multiperson, self-contained subsystems for spacecraft application.

The electrochemical removal technique works as follows: CO_2 is continuously removed from a flowing cabin air stream. The removal takes place in a module consisting of a series of electrochemical cells. Each cell consists of two electrodes separated by a matrix containing an aqueous carbonate electrolyte solution. Plates adjacent to the electrodes provide passageways for distribution of gases and electrical current. Figure 1 shows a functional schematic of the Electrochemical Depolarized CO_2 Concentrator (EDC) cell while Figure 2 details the specific electrochemical and chemical reactions. As shown in Figure 2, the overall reaction is:

$$O_2 + 2CO_2 + 2H_2 = 2CO_2 + 2H_2O + \text{electrical energy} + \text{heat} \qquad (1)$$

Two moles of CO_2 are theoretically transferred for one mole of O_2 consumed. The observed ratio of CO_2 transferred to O_2 consumed represents the process removal efficiency with a defined efficiency of 100% occurring when 2.75 kg (6.05 lb) of CO_2 is removed for each kg (2.2 lb) of O_2 consumed.

(1,2) References cited at the end of this report.

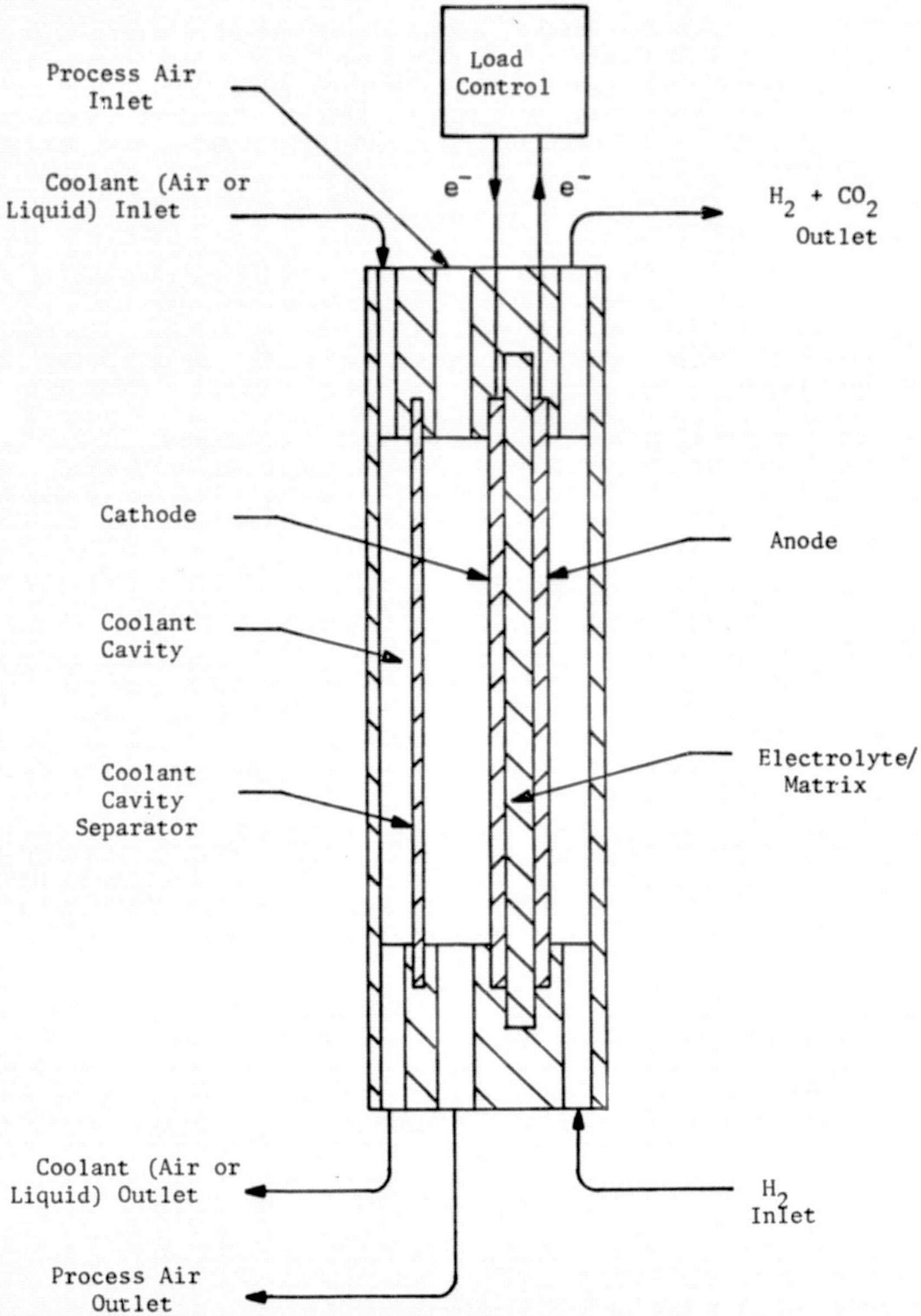
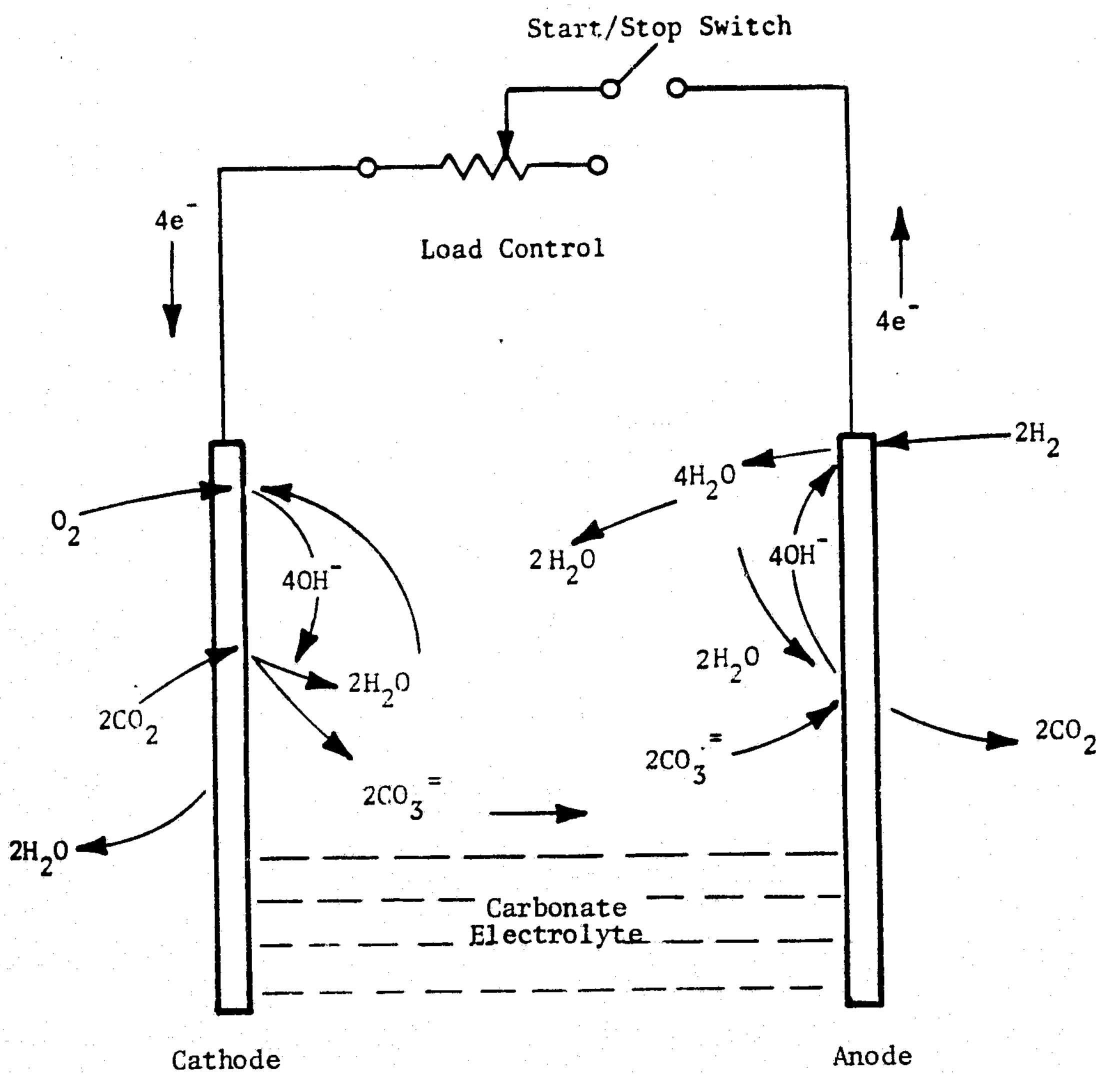


FIGURE 1 EDC CELL FUNCTIONAL SCHEMATIC



Cathode Reactions:

$$O_2 + 2H_2O + 4e^- = 4OH^-$$
$$4OH^- + 2CO_2 = 2H_2O + 2CO_3^=$$

Anode Reactions:

$$2H_2 + 4OH^- = 4H_2O + 4e^-$$
$$2CO_3^= + 2H_2O = 4OH^- + 2CO_2$$

Overall Reaction:

$$O_2 + 2CO_2 + 2H_2 = 2CO_2 + 2H_2O + \text{Electrical Energy} + \text{Heat}$$

FIGURE 2 EDC ELECTROCHEMICAL AND CHEMICAL REACTIONS

Program Objectives

The overall objectives of the present program are to (1) improve the performance of the electrochemical CO_2 removal technique by increasing CO_2 removal efficiencies at pCO_2 levels below 400 Pa (3 mm Hg), increasing cell power output and broadening the tolerance of electrochemical cells for operation over wide ranges of cabin relative humidity (RH); (2) design, fabricate and assemble development hardware to continue the evolution of the electrochemical concentrating technique from the existing level to an advanced level able to efficiently meet the CO_2 removal needs of a spacecraft Air Revitalization System (ARS); (3) develop and incorporate into the EDC the components and concepts that allow for the efficient integration of the electrochemical technique with other subsystems to form a spacecraft ARS, (4) combine ARS functions to enable the elimination of subsystem components and interfaces and (5) demonstrate the integration concepts through actual operation of a functionally-integrated ARS.

Program Organization

To meet the above objectives, the program has been divided into five tasks plus documentation and program management functions. The five tasks are:

1.0 Design, fabricate and assemble development hardware to evolve the EDC's technology from the existing level to an advanced level capable of efficiently removing CO_2 from a spacecraft's atmosphere and able to be integrated with other Environmental Control/Life Support System (EC/LSS) subsystems to form a spacecraft ARS.

2.0 Design, develop, fabricate, assemble, functionally check out and calibrate Test Support Accessories (TSA) to be compatible with the test objectives of the subsystem hardware and the supporting research and technology test program.

3.0 Establish, implement and maintain a mini-Product Assurance program through all phases of contractual performance including design, fabrication, purchasing, assembly, testing, packaging and shipment consistent with a program in the early stages of development.

4.0 Perform a variety of subsystem and integrated system/subsystem testing required to demonstrate readiness of the EDC concept.

5.0 Complete essential and desirable supporting research and development efforts to further expand the technology base associated with the spacecraft EDC. Special emphasis shall be placed on the development of the electrochemical cell: the electrodes, the electrolyte retaining matrix and the electrolyte.

Report Organization

This Annual Report covers the work performed during the period March, 1977 through January, 1978. The following five sections present the technical results grouped according to (1) Subsystem Developments, (2) TSA Developments, (3) Mini-Product Assurance Program (4) Program Testing and (5) Supporting Technology Studies. These sections are followed by Conclusions and Recommendations based on the work performed.

SUBSYSTEM DEVELOPMENTS

The subsystem development activities performed as part of this program during the past calendar year were the design, fabrication and assembly of a liquid-cooled EDC combined with other components required to perform the functions of process air humidity control, CO_2 reduction and product water handling and distribution. Development of centralized Control/Monitor Instrumentation (C/M I) hardware was also included. This hardware was developed for integration with other EC/LSS subsystem functions, such as O_2 and nitrogen (N_2) generation, being developed under other NASA Ames Research Center Contracts,[12,13] to form an experimental, one-person Air Revitalization System (ARX-1).

One-Person Air Revitalization System

Activities completed previously as part of this program had shown that an EDC, a Sabatier-based CO_2 Reduction Subsystem (S-CRS) and an O_2 Generation Subsystem (OGS) can be successfully integrated into a laboratory breadboard O_2 Recovery System (ORS) at the one-person level.[11] Thirty days of endurance testing of the ORS showed that the three subsystems would remove and reduce metabolically-generated CO_2 and produce the required O_2 levels for one person.

The next step in the development of the EDC for spacecraft ARS application was completed as part of the program activities reported herein. The philosophy for this "next-step" approach was different than in the previously integrated laboratory breadboard system where each of the three subsystems: (1) were self-contained, (2) had their own C/M I, (3) were started and shut down independently, (4) were tied together by appropriate interfaces and (5) contained redundant components.

The self-contained system versus subsystem approach selected for the ARX-1 was based on eliminating subsystem interfaces, eliminating redundant components and utilizing the products (heat, electrical power, fluids) of one subsystem in another. Also, the C/M I was designed as a single unit that would operate all components as a single system by providing for one-button startup/shutdown of all ARS functions, automatic sequencing and control and monitoring for self-protection and safe operation.

The concept of a self-contained ARS (at the system level) is shown in block diagram form in Figure 3, while the advantages of this approach are listed in Table 1. Shown in Figure 3 are the three principal subsystems needed to remove CO_2 from and provide O_2 to the crew space. These are the EDC, S-CRS and the OGS. Oxygen and H_2 are generated through the electrolysis of water by the OGS. Carbon dioxide is stripped from the cabin atmosphere by the EDC and is sent mixed with H_2 to the S-CRS. The S-CRS reduces the CO_2 to form methane (CH_4) and water. The water is returned to the OGS for subsequent regeneration of O_2 and H_2.

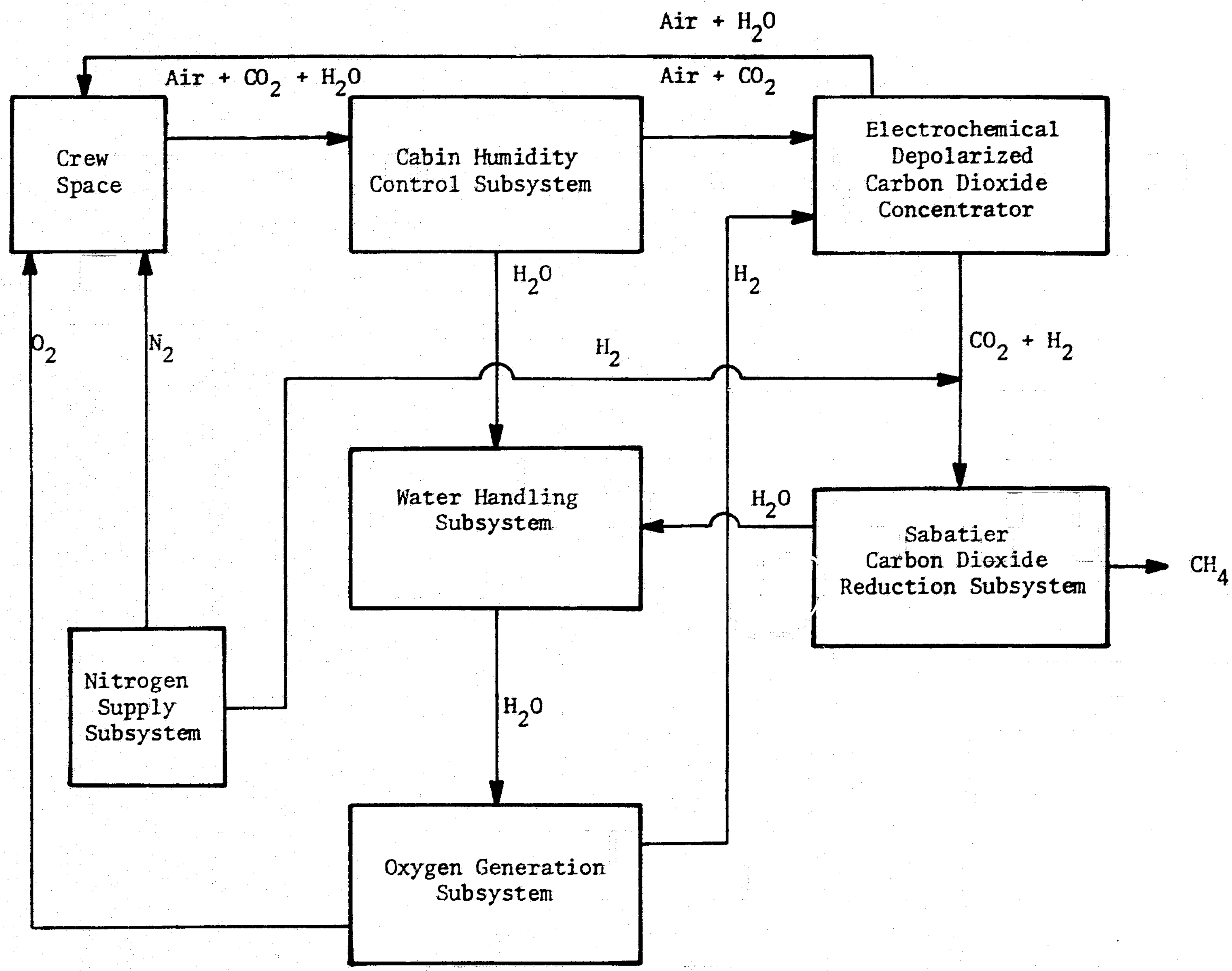


FIGURE 3 AIR REVITALIZATION SYSTEM BLOCK DIAGRAM

TABLE 1 ADVANTAGES OF DEVELOPING AND TESTING SELF-CONTAINED SYSTEM HARDWARE

Advantage	Examples
1. Elimination of duplicate components	• Single blower supplies air to CHCS and EDC • Common shutoff, purge and isolation valves • Single regulator backpressures S-CRS and EDC exhaust gases • Water accumulators, valves and pumps for S-CRS and CHCS combined • Single blower cools S-CRS reactor and separates entrained liquid from CHCS process air • Series and parallel flow of coolant minimizes valves, lines and fittings
2. Reduction of TSA hardware, interfaces and expendables	• H_2 from OGS used in EDC and S-CRS • Water collected from CHCS and S-CRS used in OGS • Single power interface • EDC process air from CHCS instead of TSA • H_2 plus CO_2 mixture for S-CRS from EDC
3. Centralized Control and Monitor Instrumentation	• Single C/M I operator/system interface panel • One-button startup and shutdown for integrated system
4. Provides real-life test conditions	• Transient performance evaluated • Simultaneous testing of subsystems and components • Early development problems uncovered - not only major ones, but also those often overlooked, e.g., coolant and water handling • Interaction between major components identified
5. "Single System" philosophy provides technology base for actual flight hardware	• No surprises when adding ancillary and interface components later on
6. Saves development costs	• Hardware components eliminated • Test personnel time minimized • Expendable fluids minimized

Other subsystems and components are needed to provide a more complete air revitalization function. A N_2 Supply Subsystem (NSS) using decomposition of hydrazine (N_2H_4) provides for N_2 lost through cabin leakage. Also, the NSS supplies extra H_2 required by the S-CRS. A Cabin Humidity Control Subsystem (CHCS) is used to supply conditioned air to the EDC at tight RH interfaces for optimum efficiency and to remove the metabolic- and EDC-produced moisture from the cabin air. A Water Handling Subsystem (WHS) collects, stores and distributes liquid water within the ARS. Coolant flow components (not shown in Figure 3) distribute spacecraft-provided liquid coolant throughout the ARS. Finally, the centralized C/M I provides for automatic, integrated operation.

Table 2 lists the design specifications and characteristics established for the ARX-1. Each of the elements of the ARX-1, with the exception of the OGS and NSS, are discussed in the following subsections. The activities associated with the development of the OGS and NSS for the ARX-1 are funded under separate NASA Ames Research Center programs.[12,13] The development associated with the S-CRS and its major components was supported by Contractor funds. Only the testing and general integration aspects are being performed under this contract.

CO_2 Removal/Cabin Humidity Control Subsystem Hardware

Previous EDC testing had shown that substantially higher cell voltages and higher CO_2 removal efficiencies, particularly at low pCO_2 levels, could be achieved with liquid-cooled cells compared to air-cooled cells.[10] The liquid-cooled concept lends itself well to the centralized ARS approach especially when integrated with a humidity control concept using a condensing heat exchanger. As a result, the liquid-cooled EDC concept combined with the cabin humidity control function was selected for the ARX-1. Other reasons for closely grouping the CO_2 removal and cabin air moisture control are that the major components interface directly with a flowing stream of cabin air and the air processed by a condensing heat exchanger is ideally suited for achieving reliable and efficient EDC operation.

Figure 4 is a block diagram of the combined EDC/CHCS functions. Filtered cabin air enters a condensing heat exchanger where moisture is removed to control the cabin dew point. A portion of the air passes through the EDC Module (EDCM) for CO_2 removal. The EDC exhaust air and the remaining process air are returned to the cabin. The moisture removed by the condensing heat exchanger, along with some cabin air, is passed to the WHS components. Hydrogen required by the EDC is obtained from the OGS and is sent mixed with the CO_2 to the S-CRS. A N_2 purge of the H_2-carrying cavities of the EDC is provided. Oxygen from the OGS and make-up N_2 from the NSS are added to the air upstream of a filter prior to delivery to the cabin.

An EDCM consisting of six advanced liquid-cooled cells was fabricated. Figure 5 shows a functional schematic of the internally liquid-cooled advanced cell while Figure 6 shows the parts that make up the cell. Figure 7 is a photograph of the assembled six-cell module.

The major component of the CHCS is the condensing heat exchanger shown in Figure 8. The heat exchanger contains a zero-gravity compatible liquid/gas separating section.[11]

TABLE 2 ONE-PERSON AIR REVITALIZATION SYSTEM DESIGN CHARACTERISTICS

Crew Size	1
CO_2 Removal Rate, kg/d (lb/d)	1.00 (2.20)
O_2 Generation Rate, kg/d (lb/d)	1.03 (2.27)[a]
Water Vapor Removal Rate, kg/d (lb/d)	1.80 (3.96)
Liquid Water Production Rate, kg/d (lb/d)	1.49 (3.27)
Methane Production Rate, kg/d (lb/d)	0.36 (0.79)
Nitrogen Production Rate, kg/d (lb/d)	0.60 (1.32)

(a) Consists of 0.84 kg/d (1.84 lb/d) O_2 metabolic and 0.19 kg/d (0.43 lb/d) for leakage requirements.

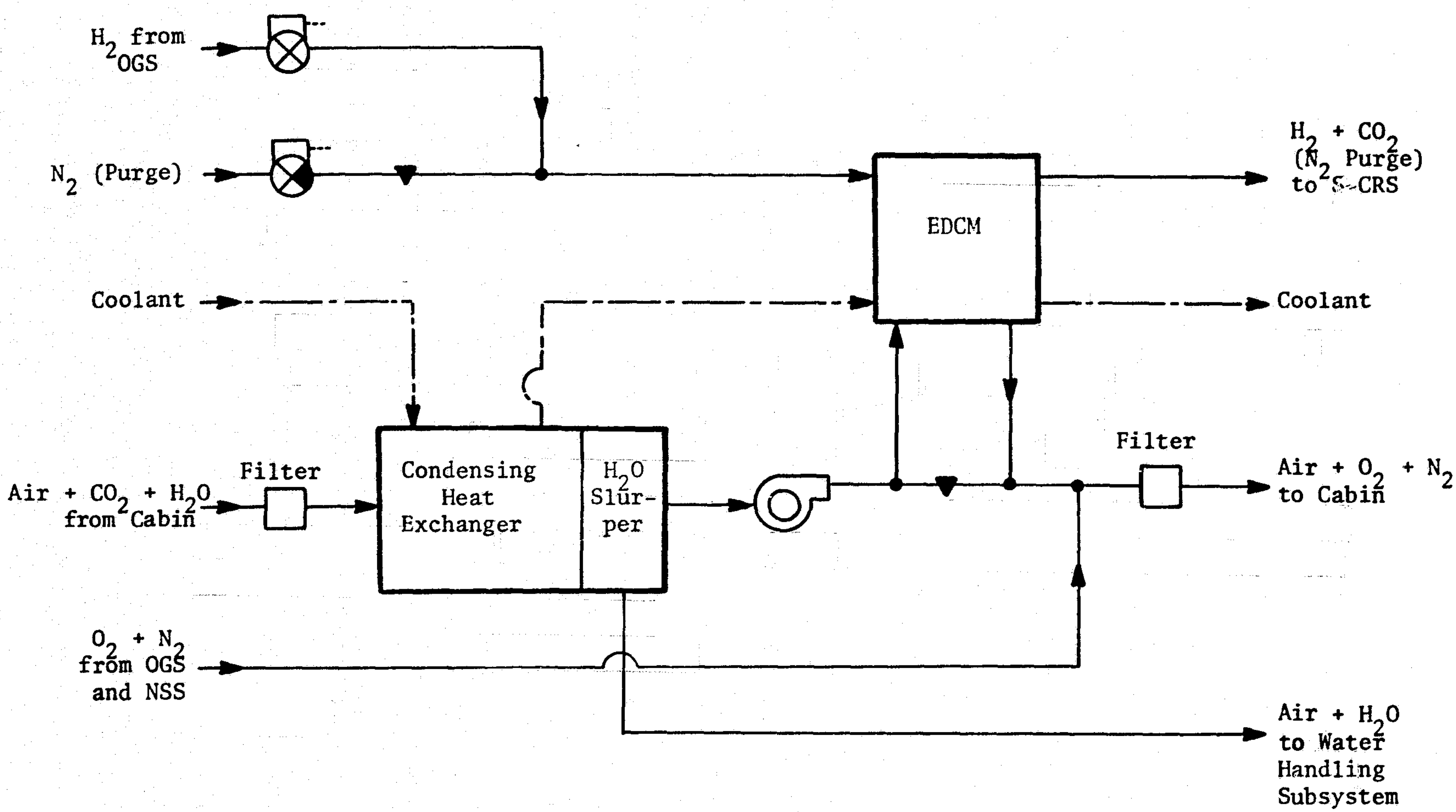


FIGURE 4 EDC/CHCS BLOCK DIAGRAM

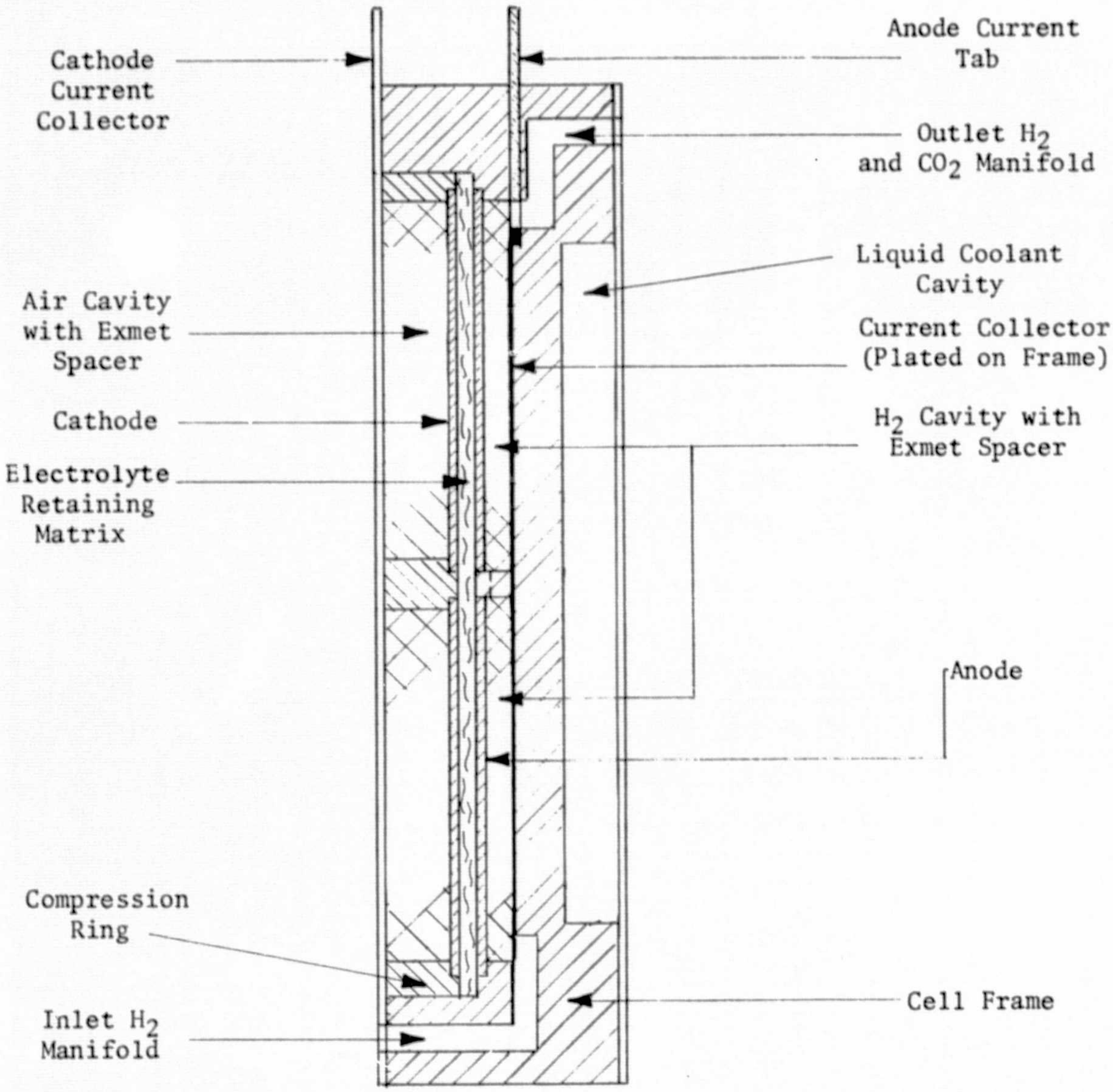


FIGURE 5 ADVANCED LIQUID-COOLED EDC CELL FUNCTIONAL SCHEMATIC

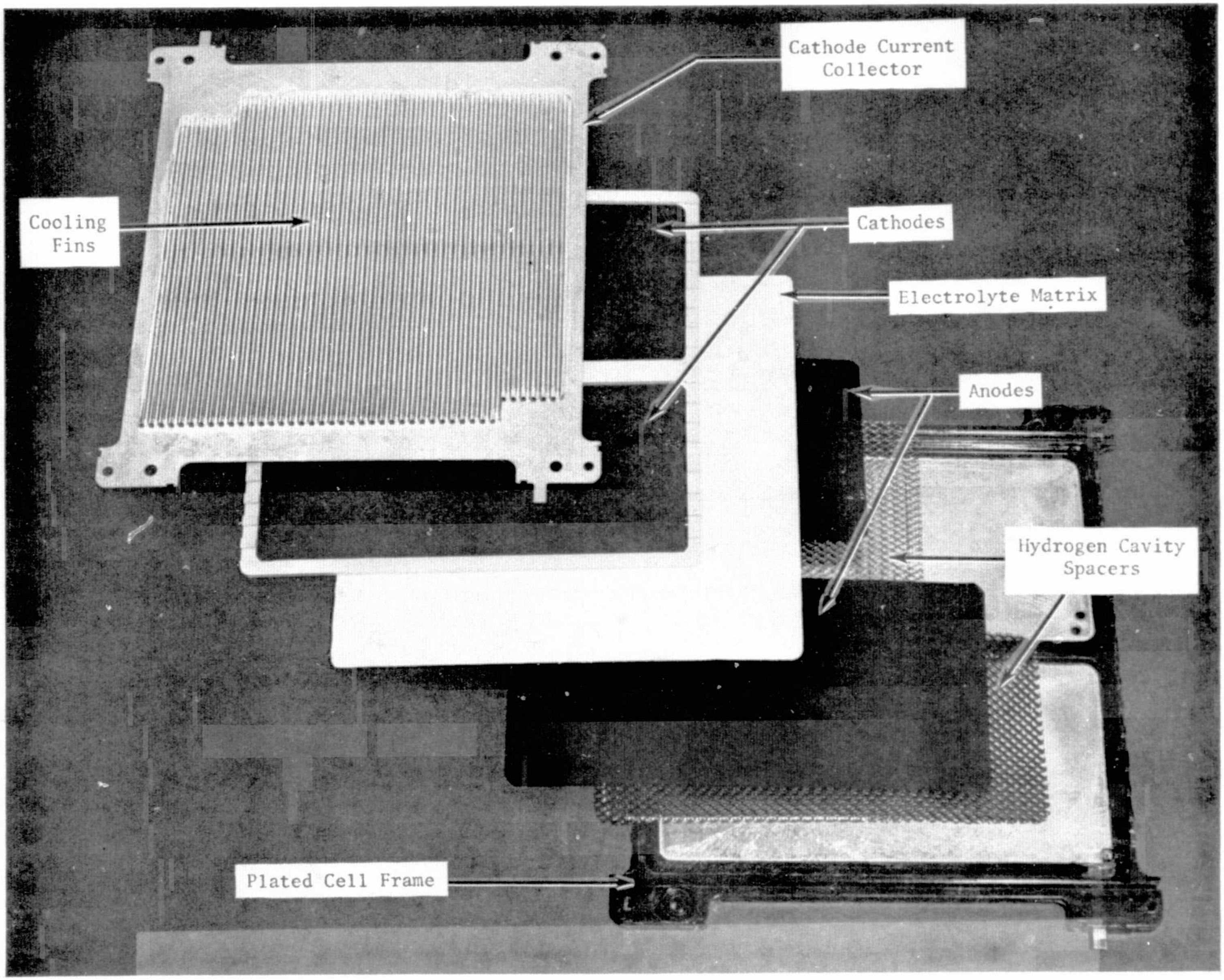


FIGURE 6 ADVANCED EDC LIQUID-COOLED CELL PARTS

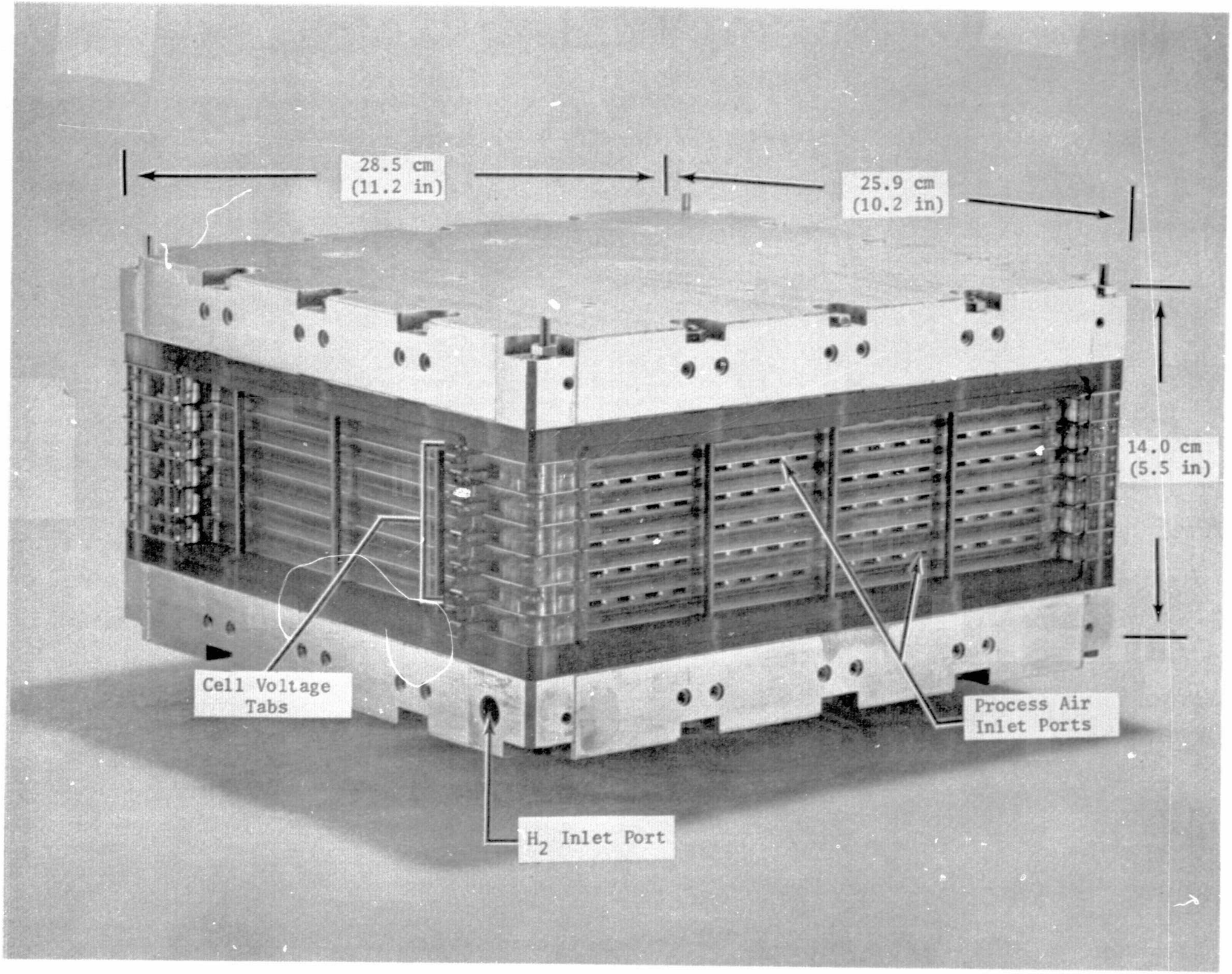


FIGURE 7 SIX-CELL LIQUID-COOLED EDCM

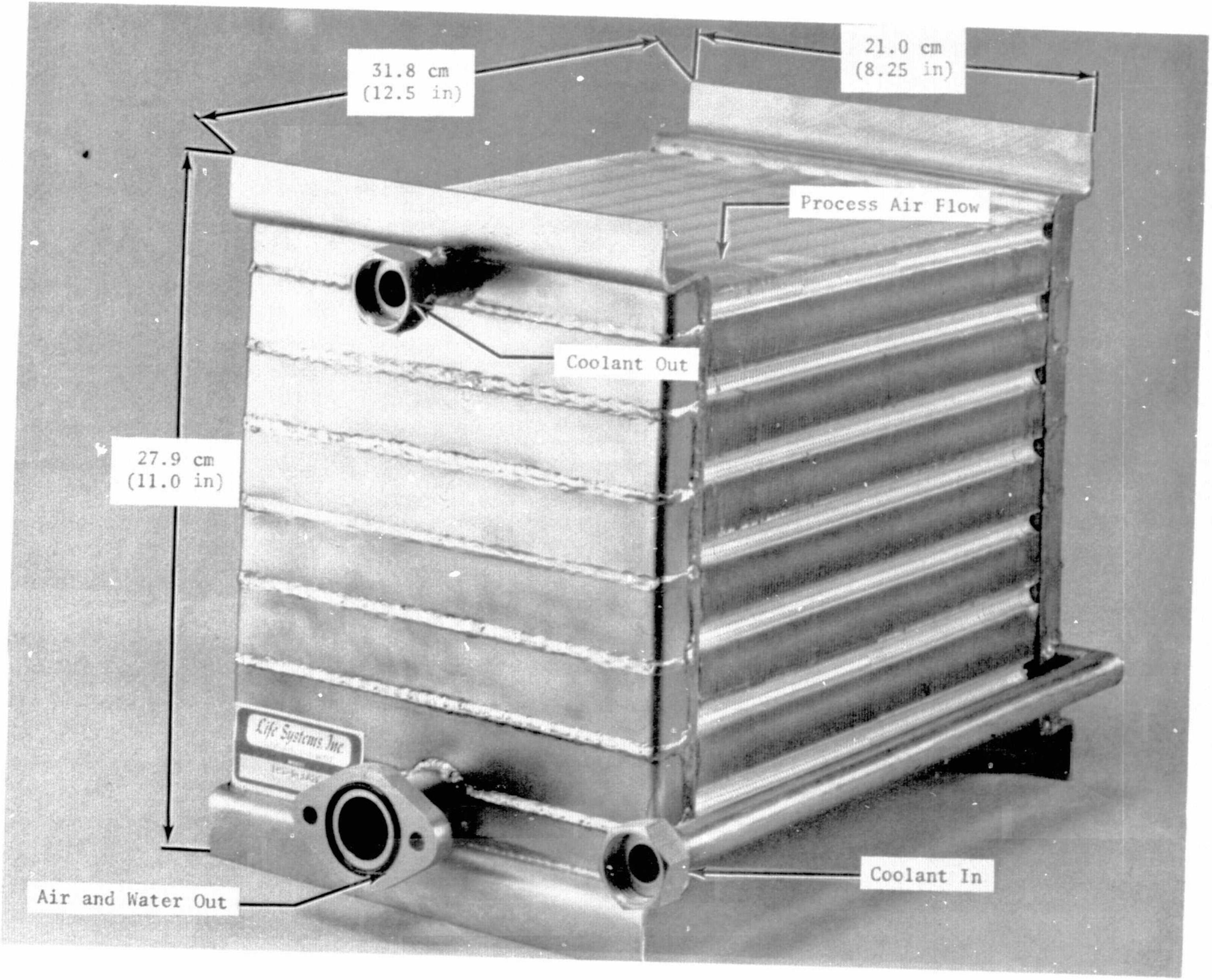


FIGURE 8 ONE-PERSON CONDENSING HEAT EXCHANGER

Fabrication of all ancillary components and packaging of the EDC/CHCS mechanical hardware have been completed and the combined unit is ready for testing as part of the ARX-1. The baseline operating conditions for the EDC/CHCS tests have been established. These conditions are listed in Table 3.

CO_2 Reduction Subsystem Hardware

The Sabatier-based CO_2 reduction process was selected for the ARX-1. This process is ideally suited for an ARS using a N_2H_4 based NSS which produces H_2 as a byproduct. Sufficient H_2 is then available to convert all of the metabolic CO_2 for subsequent O_2 recovery. The Sabatier process is based on the reaction of

$$4H_2 + CO_2 = 2H_2O + CH_4 + \text{heat} \qquad (2)$$

Figure 9 is a block diagram of the S-CRS. Carbon dioxide and H_2 from the EDC enter the Sabatier reactor where the reactants undergo conversion to CH_4 and water. The water is condensed in a zero-gravity compatible, liquid-cooled porous plaque condenser/separator and is removed to the WHS. The reactor exhaust gases, primarily CH_4, are passed to an Attitude Control System (ACS) or storage. However, provisions have been made for venting the product gases minus the water to overboard vacuum. A vent to cabin, following a N_2 safety purge, is provided to depressurize the S-CRS for maintenance. The Sabatier reactor is air-cooled.

Figure 10 is a photograph of the main component of the S-CRS, the Sabatier reactor. This reactor was developed and fabricated as part of a Contractor-funded activity and was previously tested in the laboratory breadboard ORS.[11] The reactor was sized to handle the CO_2 reduction requirements from one to three persons. The anticipated performance at the one-person level is shown in Table 4.

Water Handling Subsystem Hardware

Water is being generated and consumed at various locations in the ARX-1. For purposes of the design and fabrication, the water handling components were treated as a separate subsystem. A block diagram of the WHS is shown in Figure 11. The two principal water sources are from the condensing heat exchangers in the CHCS and the S-CRS. The condensed water from the CHCS is separated from the air by a hydrophobic screen liquid/gas separator. A photograph of this component, previously developed under this program, is shown in Figure 12.[11] The water vapor in the outlet gas stream of the Sabatier reactor is condensed and separated by a porous plaque liquid/gas condenser/separator. This unit is shown in Figure 13. The liquid outputs from these two devices flow to a water accumulator which is periodically emptied into a water storage tank. As is shown in Figures 3 and 11, this liquid water is also supplied to the OGS for conversion to H_2 and O_2, thus completing the water loop.

TABLE 3 EDC/CHCS OPERATING CONDITIONS FOR ONE-PERSON AIR REVITALIZATION SYSTEM

EDC	
Number of Cells	6
CO_2 Removal Rate, kg/d (lb/d)	1.0 (2.2)
Current, A	10.3
Current Density, mA/cm^2 (ASF)	22.6 (21)
Cell Voltage, V	0.45
Air Inlet Temperature, K (F)	285 to 290 (54 to 63)
Pressure, kPa (psia)	101 (14.7)
Air Flow, dm^3/min (cfm)	270 (9.6)
pCO_2, Pa (mm Hg)	400 (3.0)
CO_2 Removal Efficiency	0.84
Power Generated, W	27.8
Heat Generated, W	49.4
CHCS	
Water Removal Rate, kg/d (lb/d)	2.30 (5.07)
Cabin Air Flow, m^3/min (cfm)	2.8 (100)
Cabin Air Temperature, K (F)	286 to 300 (65 to 80)
Cabin Min. Dew Point Temperature, K (F)	279 (42.5)
Cabin Max. Relative Humidity, %	70
Nominal Latent Heat Removed, W (BTU/h)	61.5 (210)
Nominal Sensible Heat Removed, W (BTU/h)	521 (1780)

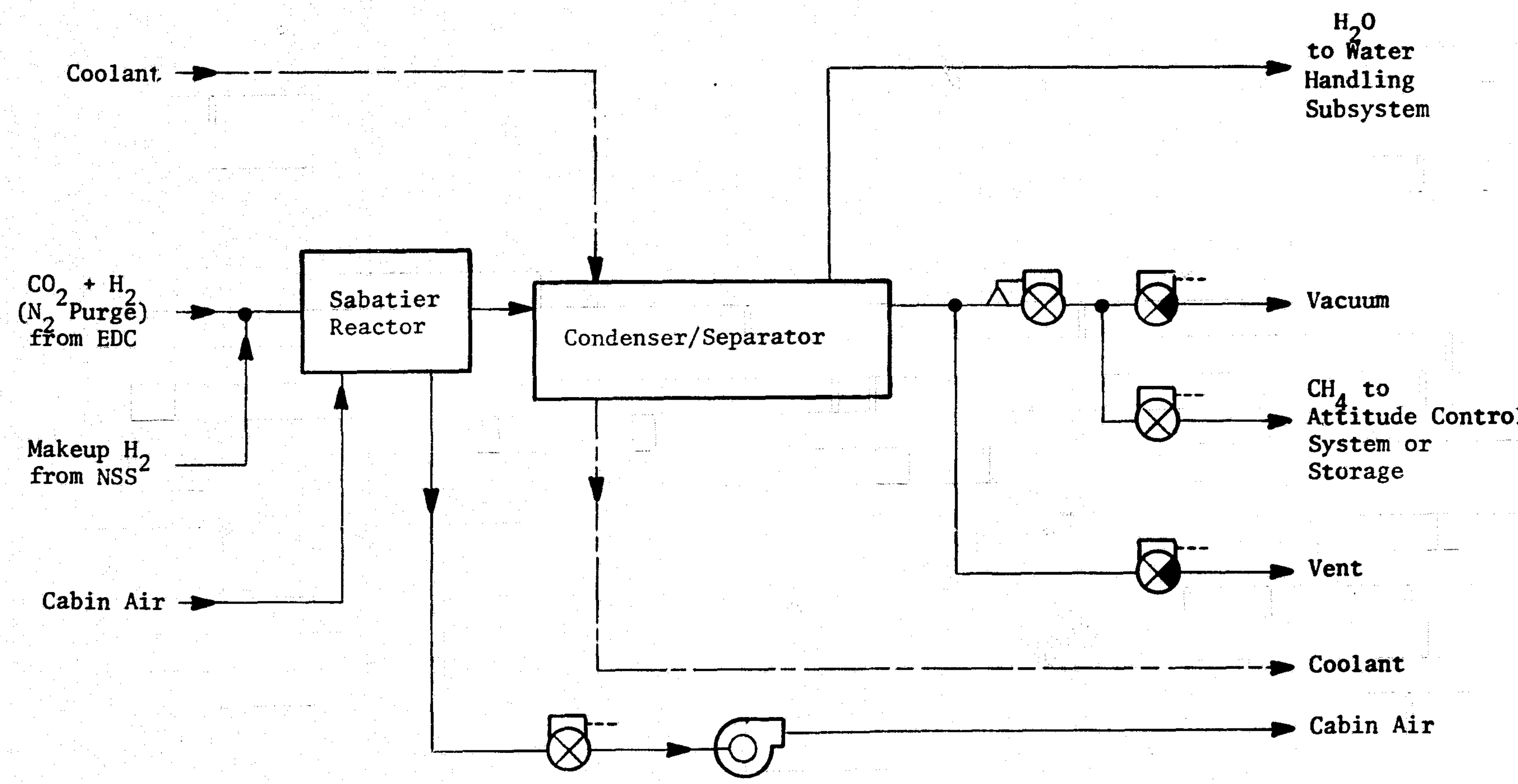


FIGURE 9 SABATIER CO_2 REDUCTION SUBSYSTEM

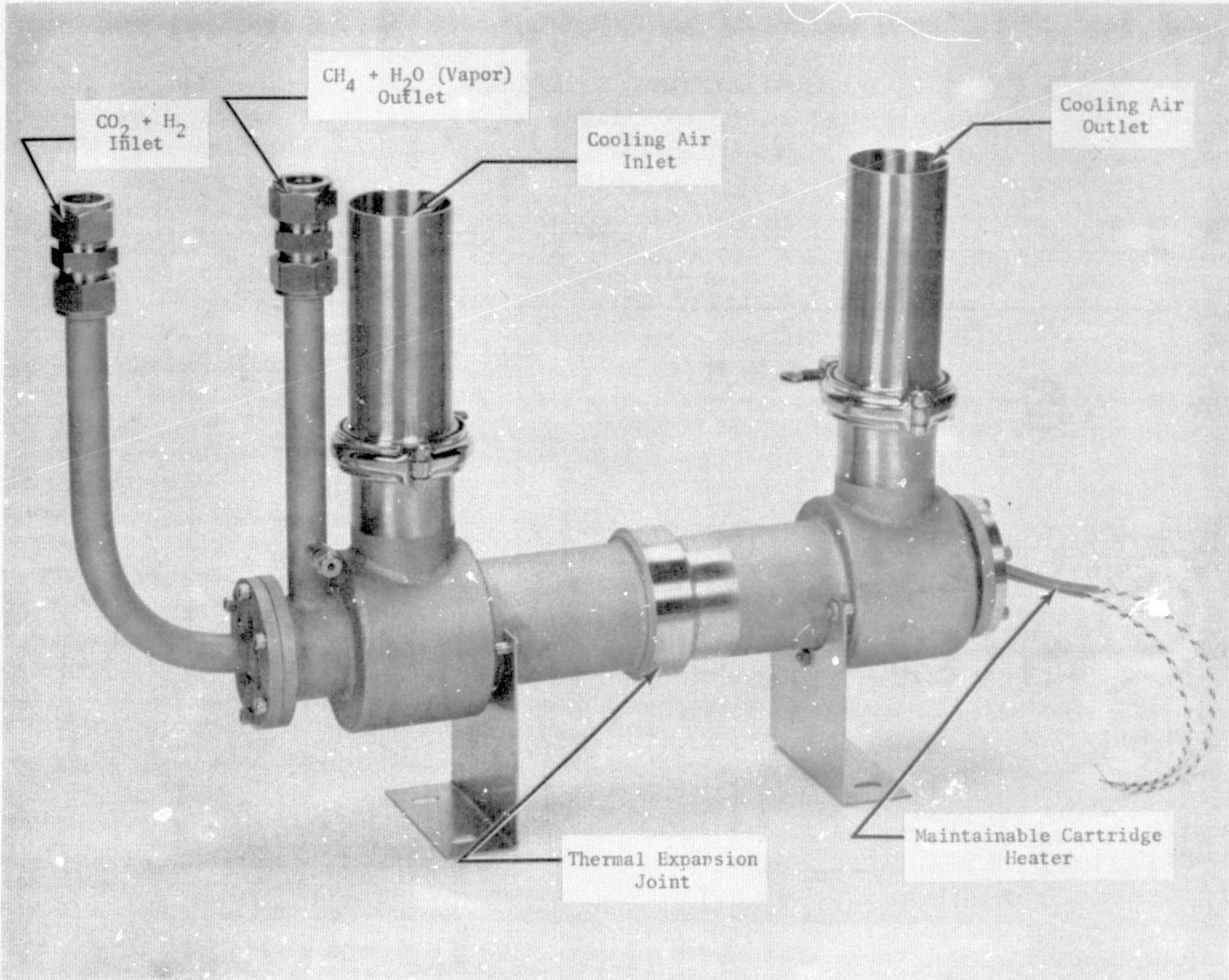


FIGURE 10 ONE- TO THREE-PERSON SABATIER REACTOR

TABLE 4 S-CRS OPERATING CONDITIONS FOR ONE-PERSON AIR REVITALIZATION SYSTEM

H_2 Inlet Flow, cm^3/min (lb/d)	1700 (0.43)
CO_2 Inlet Flow, cm^3/min (lb/d)	380 (2.20)
Water Inlet Flow, cm^3/min (lb/d)	20 (0.05)
Inlet Volumetric Flow Ratio, H_2/CO_2	4.5
H_2 Outlet Flow, cm^3/min (lb/d)	250 (0.07)
CO_2 Outlet Flow, cm^3/min (lb/d)	19 (0.11)
CH_4 Outlet Flow, cm^3/min (lb/d)	360 (0.77)
Water Outlet Flow, cm^3/min (lb/d)	730 (1.73)
Reactor Temperature, K (F)	644 (700)
Heater Temperature, K (F)	644 to 755 (700 to 900)
CO_2 Reduction Efficiency, %	95
H_2 Conversion Efficiency, %	85

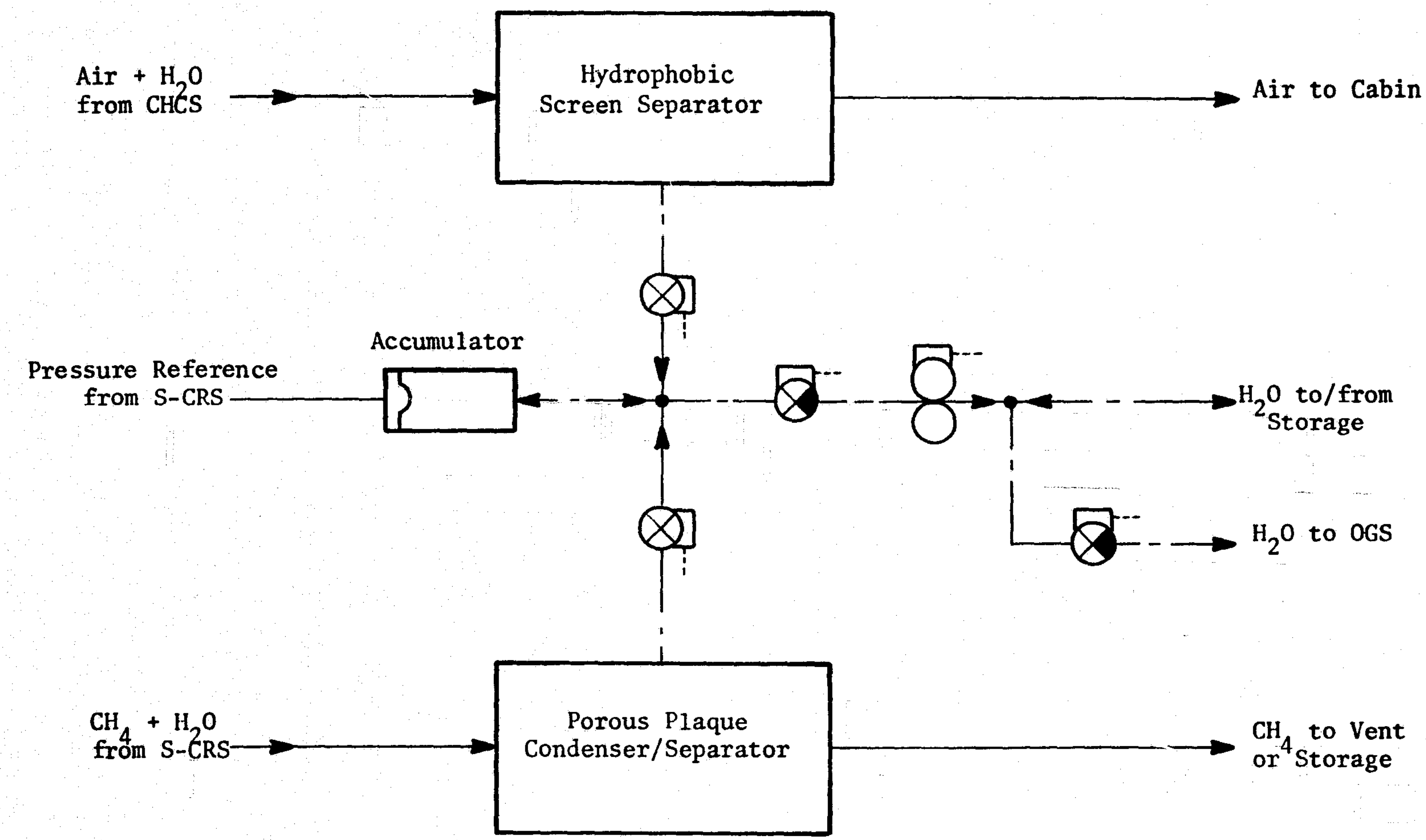


FIGURE 11 WATER HANDLING SUBSYSTEM BLOCK DIAGRAM

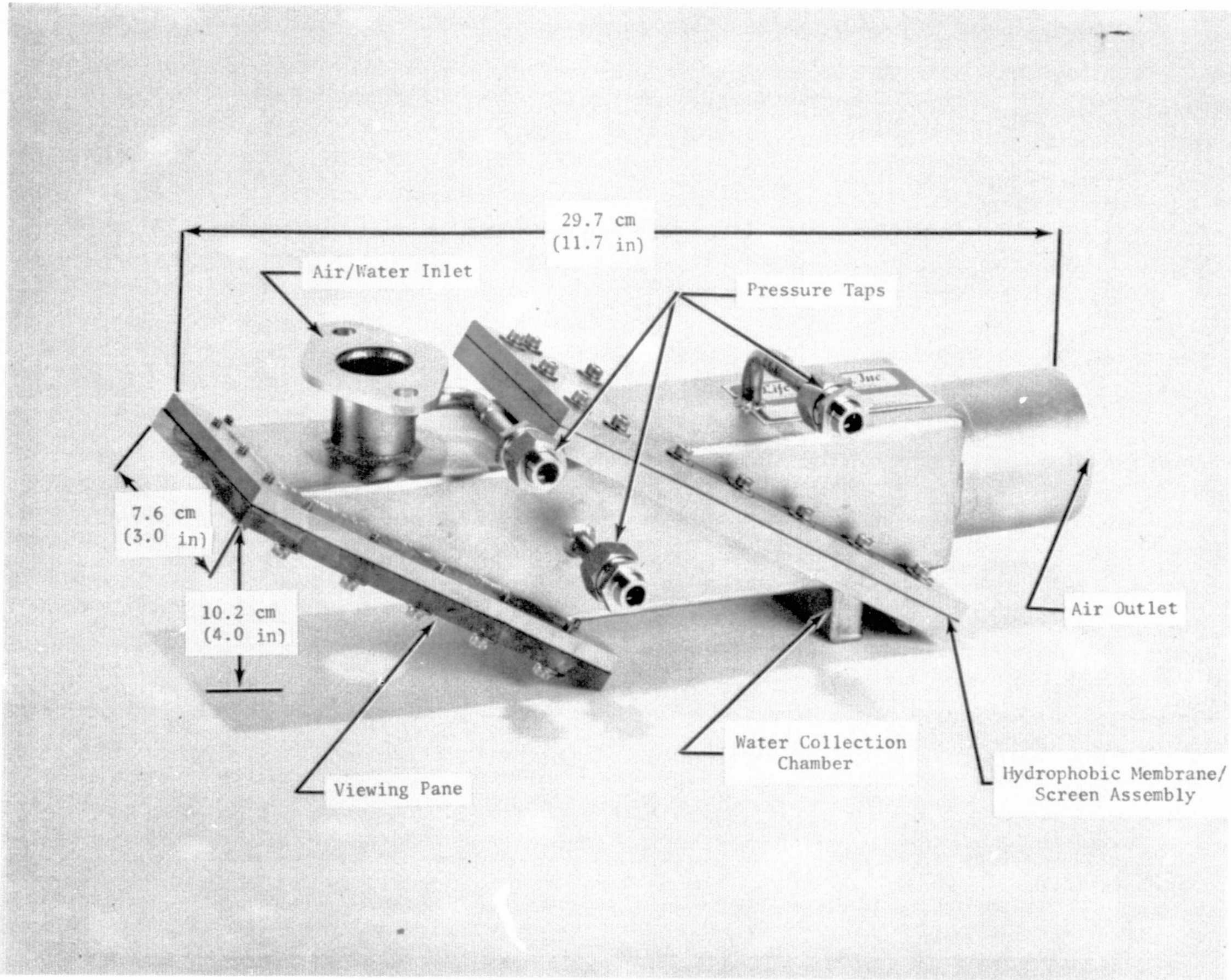


FIGURE 12 HYDROPHOBIC SCREEN SEPARATOR

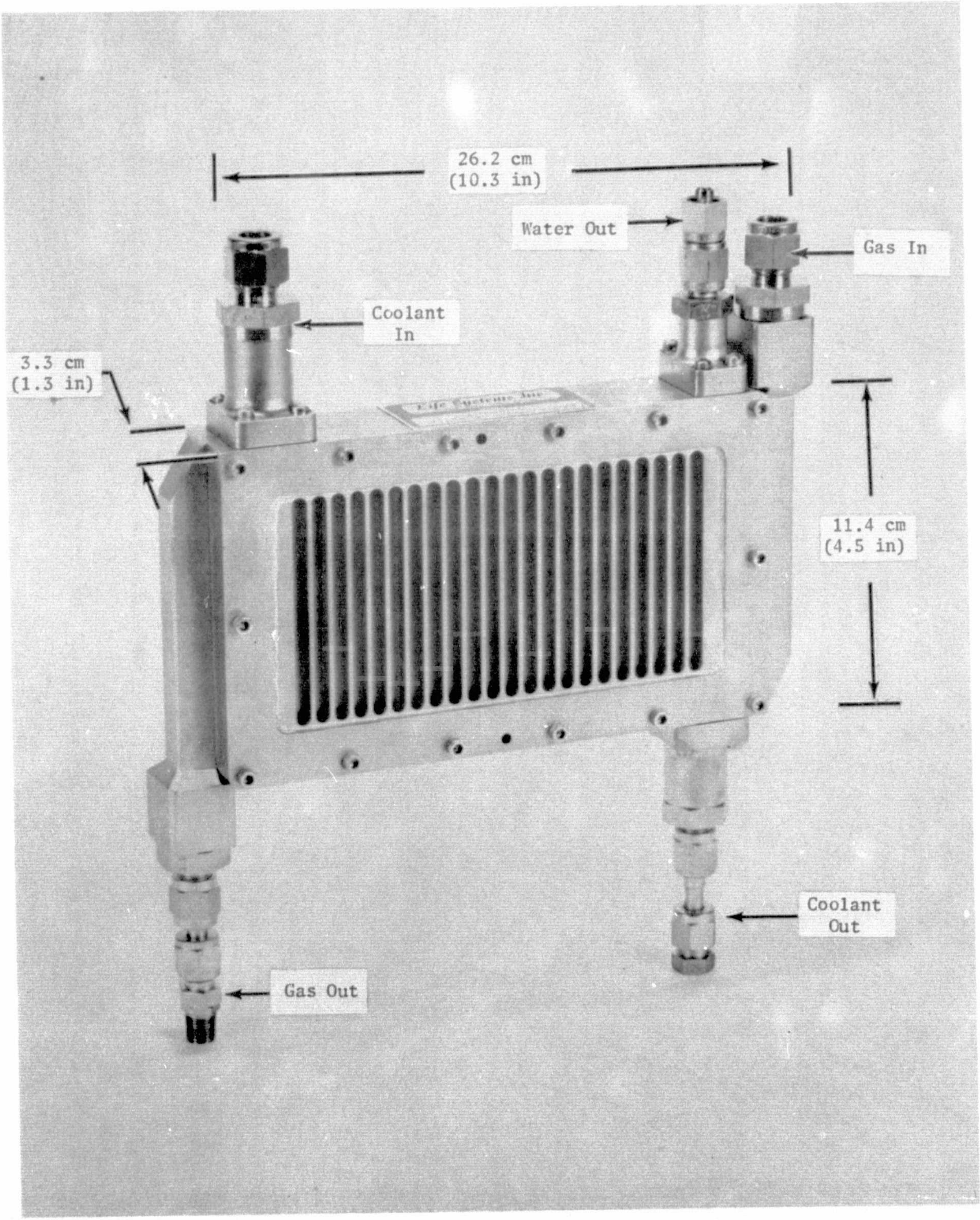


FIGURE 13 POROUS PLAQUE CONDENSER/SEPARATOR

Coolant Loop Hardware

A distinct advantage of developing a self-contained ARS is the capability for reducing the number of components and the interfaces with the TSA. One of the principal areas where this was implemented in the ARX-1 was with the liquid coolant flow and supply.

Figure 14 shows the block diagram of the coolant loop hardware. The three principal components that interface with the coolant flow are the Sabatier condenser/separator, the condensing heat exchanger in the CHCS and the EDCM heat exchanger. A combination of series/parallel flows and secondary coolant loops was designed and implemented to provide the required coolant at the desired temperatures to the proper components. A key component that permits this approach was a coolant flow diverter valve, shown in Figure 15. This component was developed under this program and has been discussed in detail in a prior report.[11]

Control/Monitor Instrumentation

The C/M I selected for the ARX-1 was an advanced instrumentation design using minicomputer/software technologies. This C/M I including an advanced operator/subsystem interface panel was designed to be packaged in a separate self-contained enclosure.

C/M I Function - The function of the C/M I is to provide: automatic mode and mode transition control, automatic shutdown provisions for self-protection, provisions for monitoring system parameters and provisions for interfacing with ground test instrumentation.

Operating Modes and Mode Transitions - The C/M I provides for five operating modes: (1) Shutdown, (2) Normal, (3) Purge, (4) Standby, (5) Unpowered. These operating modes and allowable mode transitions are shown in Figure 16. In the Normal mode, the system is providing its function of removing and reducing CO_2, generating O_2 and N_2, controlling cabin humidity and distributing or storing water, as required. In the Shutdown mode, these functions are inoperative but the system is powered and all sensors are working. During Purge, all H_2-carrying lines throughout the system are being purged with N_2. In the Standby mode, the system is powered and maintained at operating temperatures and pressures, however, actual conversion processes are not taking place. Finally, in the Unpowered mode, no electrical power is applied to the system and there are no fluid flows.

System Controls - Table 5 defines the four C/M I controls associated with the hardware integrated as part of this program. These controls are: (1) EDCM current, (2) EDCM temperature, (3) CHCS temperature and (4) Sabatier reactor temperature. A brief description of each of the controls and the actuator which performs the control function are also indicated in Table 5.

System Sensors/Monitoring - Sensors are required to interface with the C/M I to provide for control and monitoring of subsystem parameters and performance. These sensors are identified in Table 6 for the hardware discussed. In addition, Table 7 identifies subsystem parameter conditions which will call for an automatic, controlled shutdown of the system.

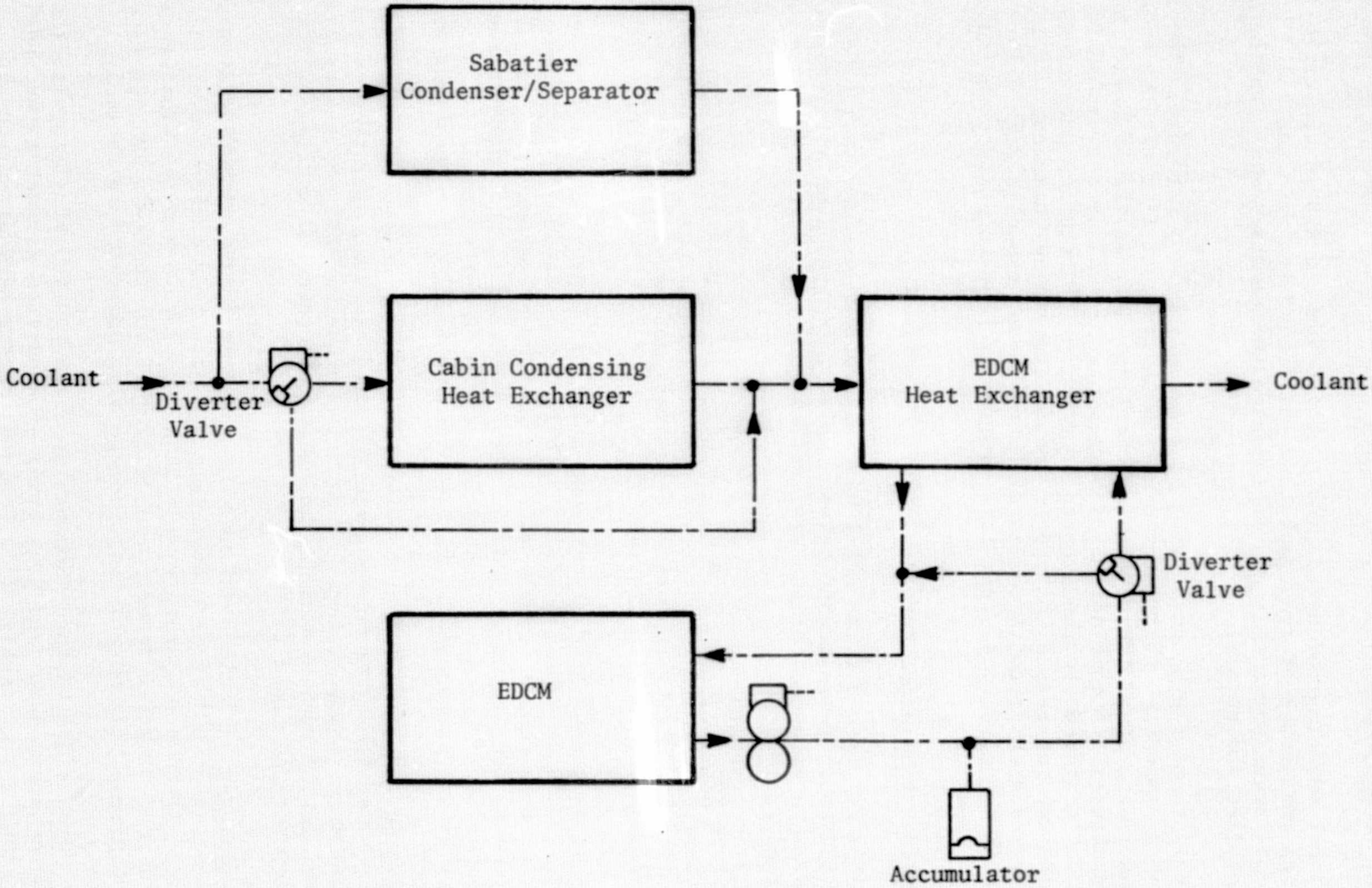


FIGURE 14 COOLANT FLOW HARDWARE BLOCK DIAGRAM

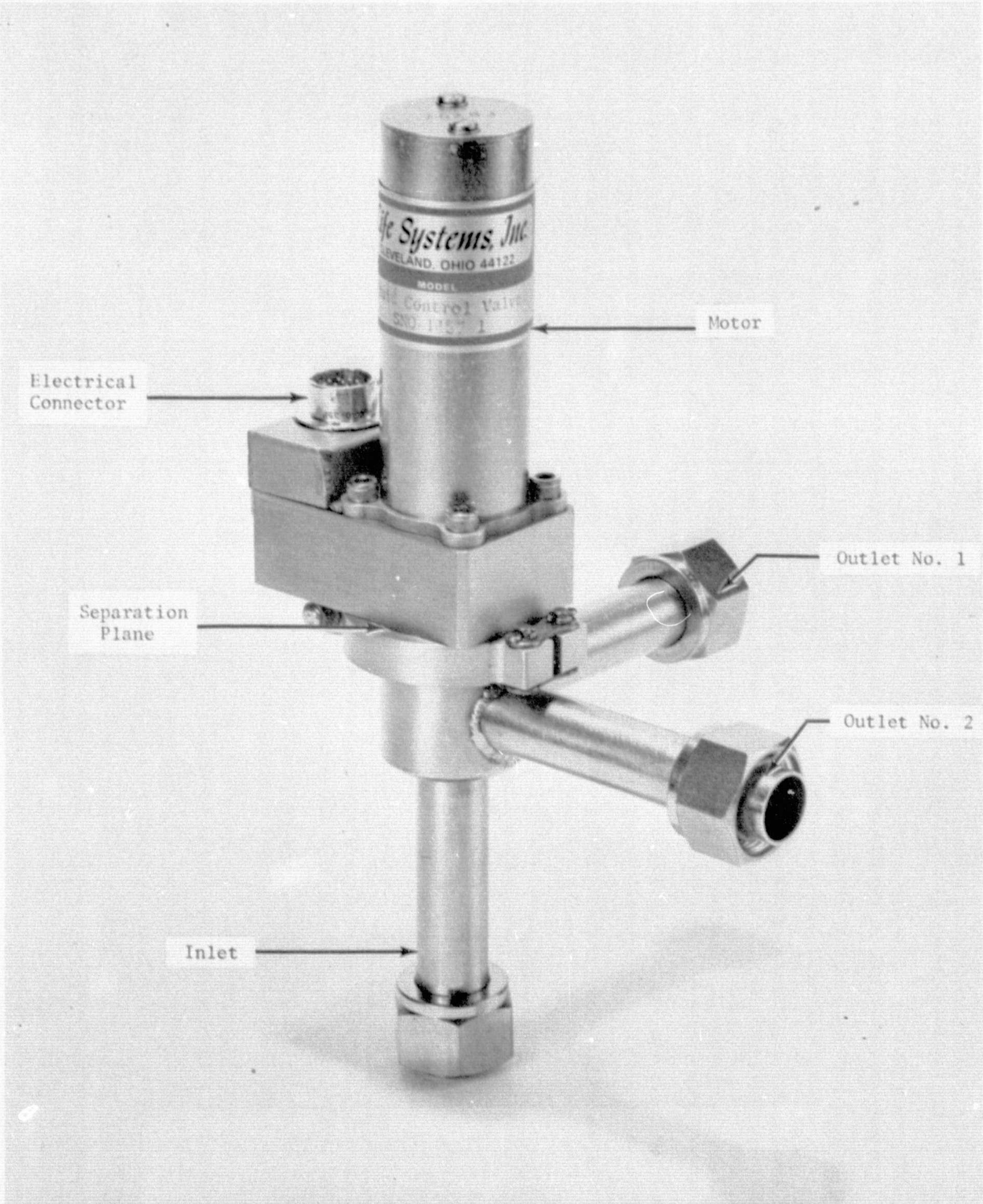
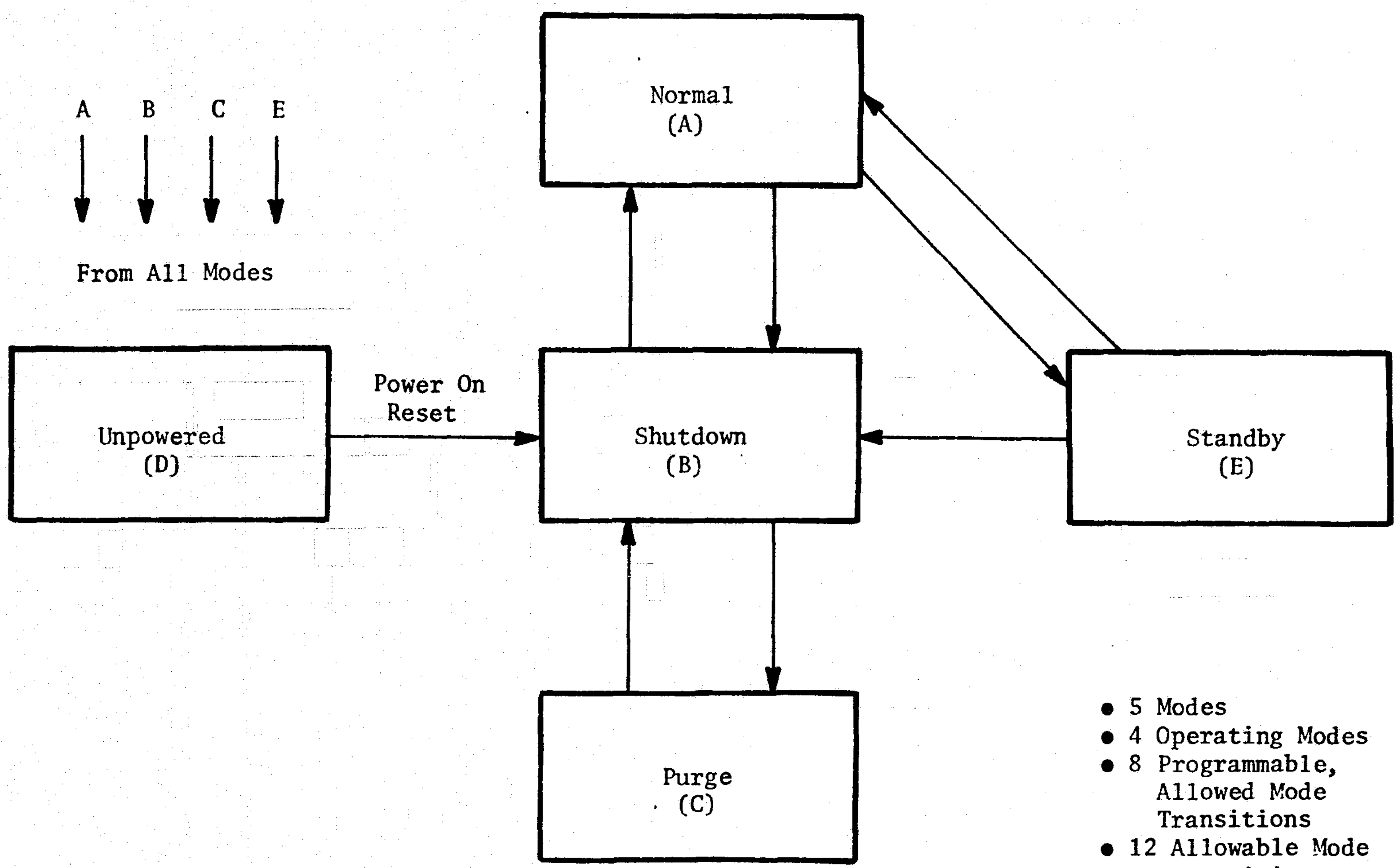


FIGURE 15 COOLANT DIVERTER VALVE



- 5 Modes
- 4 Operating Modes
- 8 Programmable, Allowed Mode Transitions
- 12 Allowable Mode Transitions

FIGURE 16 OPERATING MODES AND ALLOWABLE MODE TRANSITIONS

TABLE 5 CONTROL DEFINITIONS

Parameter Controlled	Control Description	Controlled Actuator
EDCM Current	Controls current flow through EDC cells to regulate CO_2 removal rate (set point predetermined).	Power Supply/Conditioning
EDCM Temperature	Regulates liquid coolant flow through EDCM heat exchanger to maintain desired EDCM process air outlet temperature.	Coolant Diverter Valve
CHCS Temperature	Regulates liquid coolant flow through condensing heat exchanger to maintain desired dew point temperature of cabin air.	Coolant Diverter Valve
Sabatier Reactor Temperature	Regulates cooling air flow (on/off) over reactor internal cooling fins to maintain reactor temperature profile.	Flow Control Valve

TABLE 6 SENSOR LIST

Sensor Location	Parameter Monitored	No. of Sensors
EDC/CHCS	Cabin Air Flow Rate	1
	Cabin Air Temperature	3
	Process Air Inlet Temperature	3
	Process Air Outlet Temperature	3
	Process Air Flow Rate	1
	Liquid Content in Air	1
	H_2 Supply Pressure	1
	Module Inlet Pressure	1
	H_2 Flow	1
	Cell Voltage	6
	Module Current	1
	Valve Position Indicator	2
S-CRS	H_2/CO_2 Inlet Pressure	1
	Reactor Temperature	3
	Reactor Heater Temperature	1
	Condenser/Separator Outlet Pressure	1
	Combustible Gas Contamination	3
	Exhaust Gas Pressure	1
	Valve Position Indicator	4
Water Handling Hardware	Accumulator Pressure	1
	Pump Outlet Pressure	1
	Valve Position Indicator	3
Coolant Flow Distribution Hardware	Condenser/Separator Inlet/Outlet Temperature	2
	CHCS Inlet/Outlet Temperature	2
	EDCM Outlet Temperature	1
	Valve Position Indicator	1

TABLE 7 PARAMETERS MONITORED FOR AUTOMATIC SHUTDOWN

Sensor(s) Location	Shutdown Parameter Definition
EDC	Low EDCM Cell Voltage
	High EDCM Current
	Low EDCM Current
	High EDCM Process Air Inlet Temperature
	Low EDCM Process Air Inlet Temperature
	High EDCM Process Air Outlet Temperature
	High EDCM Outlet Minus Inlet Dew Point Temperature Differential
	Low EDCM Outlet Minus Inlet Dew Point Temperature Differential
	High EDCM Inlet Minus Inlet Dew Point Temperature Differential
	Low EDCM Inlet Minus Inlet Dew Point Temperature Differential
	High EDCM H_2 Inlet Pressure
	Low EDCM H_2 Inlet Pressure
	High EDCM H_2/CO_2 Outlet Pressure
	Low EDCM H_2/CO_2 Outlet Pressure
	High EDCM H_2 Supply Pressure
	Low EDCM H_2 Supply Pressure
	High EDCM Process Air Inlet Flow
	Low EDCM Process Air Inlet Flow
	Low EDCM H_2 Inlet Flow
	High H_2 in Cabin Air Outlet
CHCS	High CHCS Heat Exchanger Coolant Outlet Temperature
	Low CHCS Heat Exchanger Coolant Outlet Temperature
	High CHCS Air Inlet Flow
	Low CHCS Air Inlet Flow
S-CRS	High Sabatier Heater Temperature
	Low Sabatier Heater Temperature
	High Sabatier Reactor Temperature
	Low Sabatier Reactor Temperature
	High Sabatier Condenser/Separator Coolant Inlet Temperature
	Low Sabatier Condenser/Separator Coolant Outlet Temperature
	High Sabatier Condenser/Separator Gas Outlet Pressure
	Low Sabatier Condenser/Separator Gas Outlet Pressure
	High Sabatier Condenser/Separator Gas Minus Water Outlet ΔP
	Low Sabatier Condenser/Separator Gas Minus Water Outlet ΔP
	High Sabatier Exhaust Pressure (to ACS or Vent)
	Low Sabatier Exhaust Pressure (to ACS or Vent)
	High H_2-in-N_2 Purge

Operator/System Interface - The operator/system interface is shown in Figure 17. The operator can communicate with the ARX-1 through this interface panel. The panel is subdivided into three major areas: System Status, System Commands and System Control.

Overall system status is provided in the upper left-hand portion of the panel. The status summary is given as Normal, Caution, Warning or Alarm and is determined by the worst case condition for any critical parameter. A reset button is provided to clear the status summary and reset the subsystem monitoring functions. Messages and information concerning the system are displayed on a cathode ray tube (CRT) located below the status summary indicators. The CRT is used to display fault diagnostic messages, present status and values of selected sensors, operator/system input/output data, operator-to-system communications, elapsed times and system-to-operator communications.

The operator commands section in the lower left-hand corner provides the capability of the operator to communicate with the C/M I. Capability exists for entering data, examining current values, updating scale factors, modifying set points or allowable ranges and control of the CRT.

Manual initiation of the four operating modes (Normal, Shutdown, Purge and Standby) is provided in the upper right-hand corner of the panel. The controls automatically prevent the operator from initiating an illegal mode transition, e.g., Normal to Purge. The subsystem will not respond to an illegal mode transition command. Accidental mode initiation is prevented by providing a mode change permit button which must be simultaneously depressed with the desired mode button.

The control status is located directly below the operating mode/commands section. Three lights are provided to indicate whether one of the automatic protection overrides or an actuator override has been activated. A light is also provided to indicate when the panel switches have been disabled, a condition used to prevent unauthorized personnel to activate any button.

Manual controls, designed primarily for use during system debug or off-design operation, are provided behind an access panel located immediately below the operator commands and system control sections (see Figure 17). Overrides are provided for all actuators in the form of toggle switches. The actuator overrides must be placed in an automatic position for the system to operate normally. Also, manual adjustments are provided for adjusting certain set points such as EDCM current and Sabatier reactor temperature. The access panel is normally closed to prevent unauthorized actuations.

Four-Person Air Revitalization System

A four-person capacity, air-cooled EDC had been modified and refurbished to be tested as part of a laboratory breadboard of an ORS. Fabrication activities had been reported during the previous reporting period.[11] Only the results of the testing are discussed as part of this report.

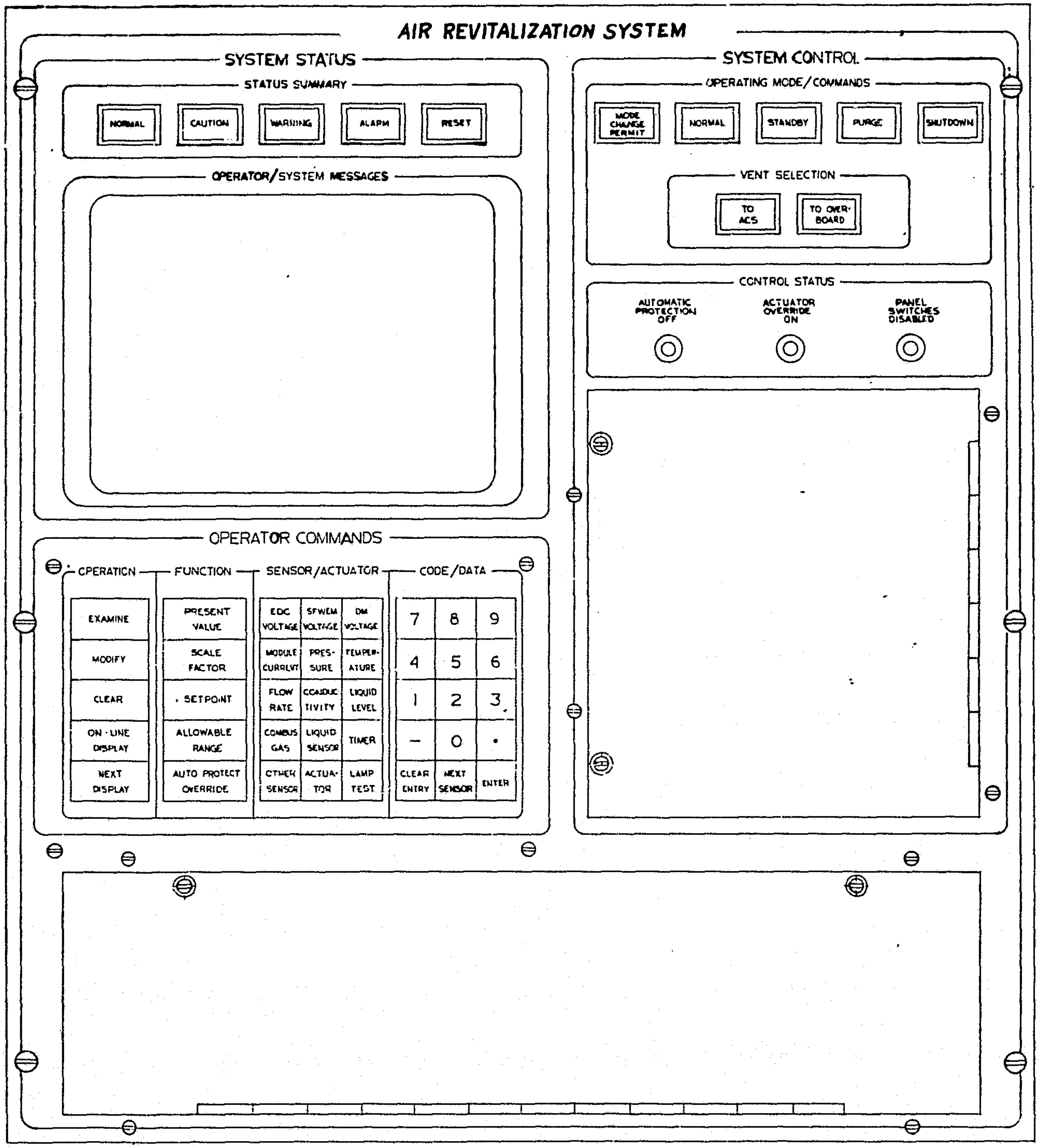


FIGURE 17 ONE-PERSON AIR REVITALIZATION SYSTEM OPERATOR/SYSTEM INTERFACE PANEL

TEST SUPPORT ACCESSORIES DEVELOPMENTS

Test Support Accessories were developed to support the planned test program of the ARX-1. A block diagram of the total TSA servicing the one-person ARS, with its C/M I and N_2H_4 Supply, is shown in Figure 18. Some of the TSA hardware was developed or refurbished as part of this program. This hardware included part or all of the Fluid Supply Unit, the Air Supply Unit (ASU) and its control, the Coolant Supply Unit, the Water Source with liquid level monitoring, the Vent/Vacuum Source, the high N_2 Pressure Supply for purging, the Data Acquisition Unit and the Parametric Data Display.

A major portion of the TSA activities were involved with the development of the Parametric Data Display. The total unit, packaged in a separate cabinet, is shown in Figure 19. It services all of the functions of the ARX-1. Specifically, it contains displays for temperatures, cell voltages and currents, flows and pressures. Also shown in the lower portion of the cabinet are power supplies required for operation of the parametric data display cabinet and the ARX-1.

MINI-PRODUCT ASSURANCE PROGRAM

A mini-Product Assurance Program was established, implemented and maintained throughout all phases of contractual performance including design, purchasing, fabrication and testing.

Quality Assurance

Quality Assurance activities were included during the design studies, interface requirement definitions and during inspection of fabricated and purchased parts. The objective was to search out quality weaknesses and provide appropriate corrective action. Also, a quality assurance effort was involved in the preparation of the Annual Report with the objective of identifying and resolving deficiencies that could affect the quality of future equipment.

Reliability

Reliability personnel participated in the program to insure (1) proper calibration of test equipment and TSA instrumentation, (2) adherence to test procedures and (3) proper recording and reporting of test data and observations. A survey of the subsystem and TSA designs was performed to determine the calibration requirements for testing. Appropriate components were calibrated during assembly and after installation.

A test procedure was established to insure that all critical parameters will be properly monitored and that the testing will conform to the program's quality assurance and safety procedures. All major testing required that a test plan be completed and reviewed.

Safety

A Safety Program was initiated to assure adherence to safety standards and procedures essential to protect personnel and equipment. The program consisted

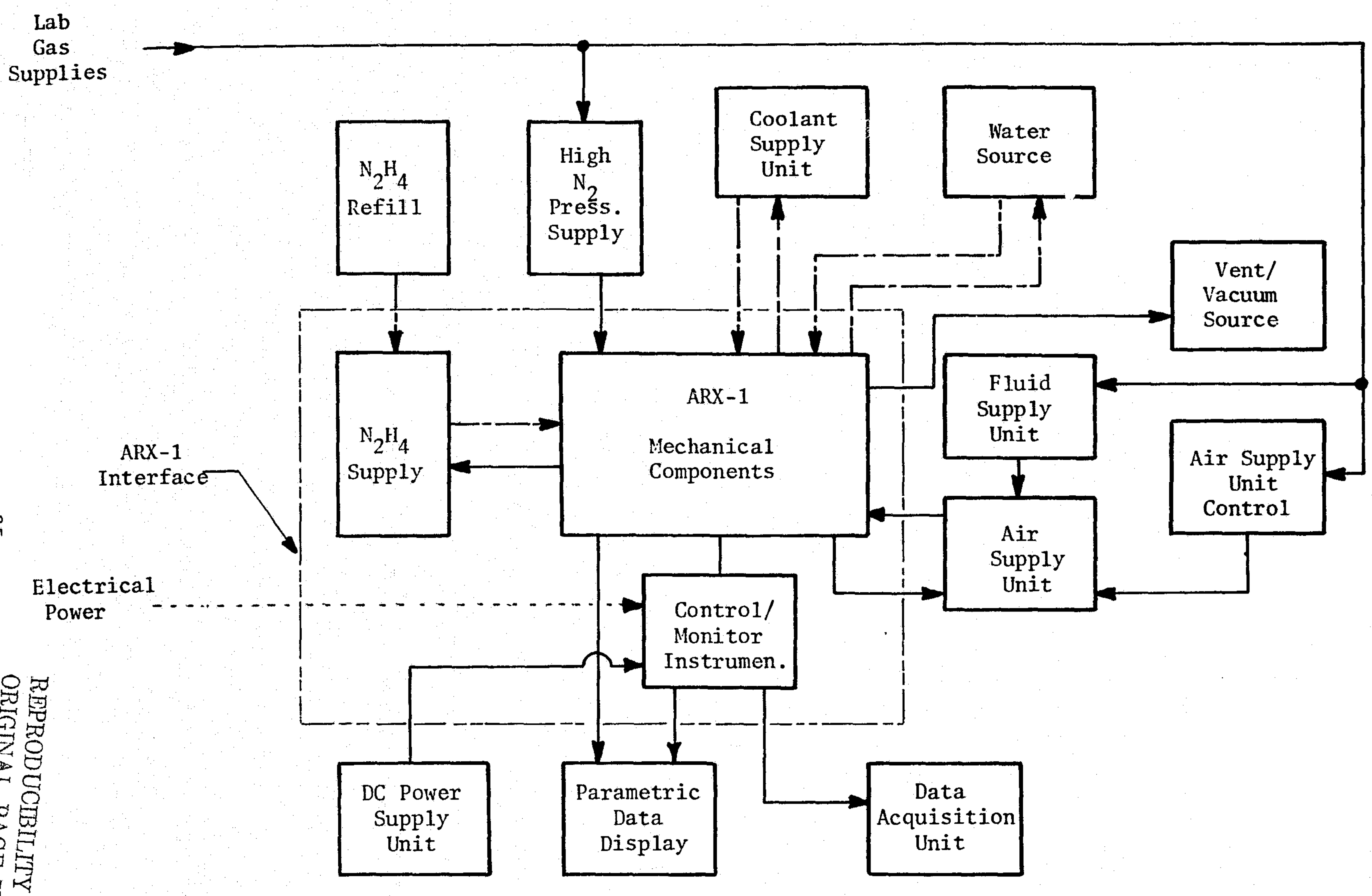


FIGURE 18 ONE-PERSON AIR REVITALIZATION SYSTEM TSA BLOCK DIAGRAM

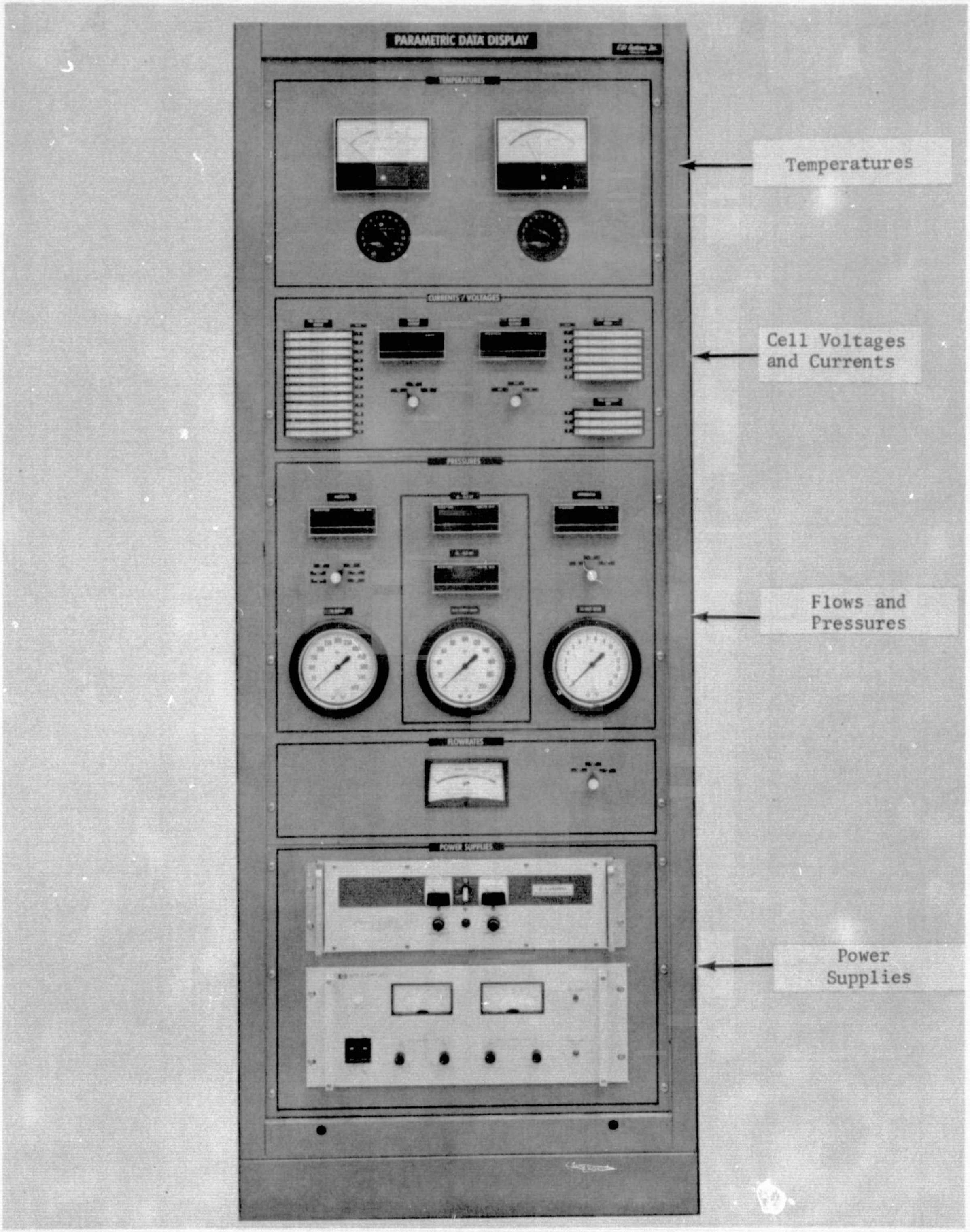


FIGURE 19 ONE-PERSON AIR REVITALIZATION SYSTEM PARAMETRIC DATA DISPLAY CABINET

of identifying possible adverse subsystem characteristics, reviewing designs and design changes for potential safety hazards, reviewing NASA Alerts for safety information and incorporating the equipment's protective features.

Materials Control

A mini-Materials Control Program was initiated to provide assurance that the ARX-1 hardware will not preclude the efficient application of a more detailed system materials control program during subsequent developments. As a goal, materials of construction were selected to comply with projected spacecraft material specifications.

Configuration Control

A mini-Configuration Management Program was established, implemented and maintained. This program provided for documentation concerning interface requirements for the ARX-1 testing. The program was implemented with a primary goal to provide assurance that the efficient application of a more detailed configuration management program can be applied during subsequent development of the ARX-1 hardware.

PROGRAM TESTING

Two subsystem level test activities were completed as part of this program: (1) testing of an air-cooled EDC as part of a laboratory breadboard Bosch-based ORS at the four-person level and (2) testing of the ASU as an environmental air simulator for the EDC and ARX-1.

Four-Person Laboratory Breadboard

Figure 20 is a block diagram showing the closed O_2 loop system with an integrated EDC, Bosch CO_2 Reduction Subsystem (B-CRS) and OGS. Details of the design of this integrated system and overall results were presented previously.[11,14]

A previously developed six-person capacity EDC[6] was refurbished and modified to form the four-person, air-cooled EDC. Only three of the six one-person design capacity modules were used to provide the CO_2 removal capacity for four persons, i.e., 4.0 kg CO_2/d (8.8 lb CO_2/d).

Table 8 lists the operating conditions and characteristics for the EDC used in testing the four-person laboratory breadboard. A total of 900 hours were accumulated through subsystem level and integrated system level testing. Figure 21 shows the overall performance of the EDC over the 900 hours of operating time. Shown are average cell voltage, CO_2 removal efficiency, current density and inlet air pCO_2 as a function of time. Successful operation of this EDC throughout the testing was in part responsible for the successful completion of the testing of a Bosch-based ORS.

Air Supply Unit

The ASU functions as an environmental air simulator. This closed-loop air supply and conditioning system is designed to simulate air temperature, gas

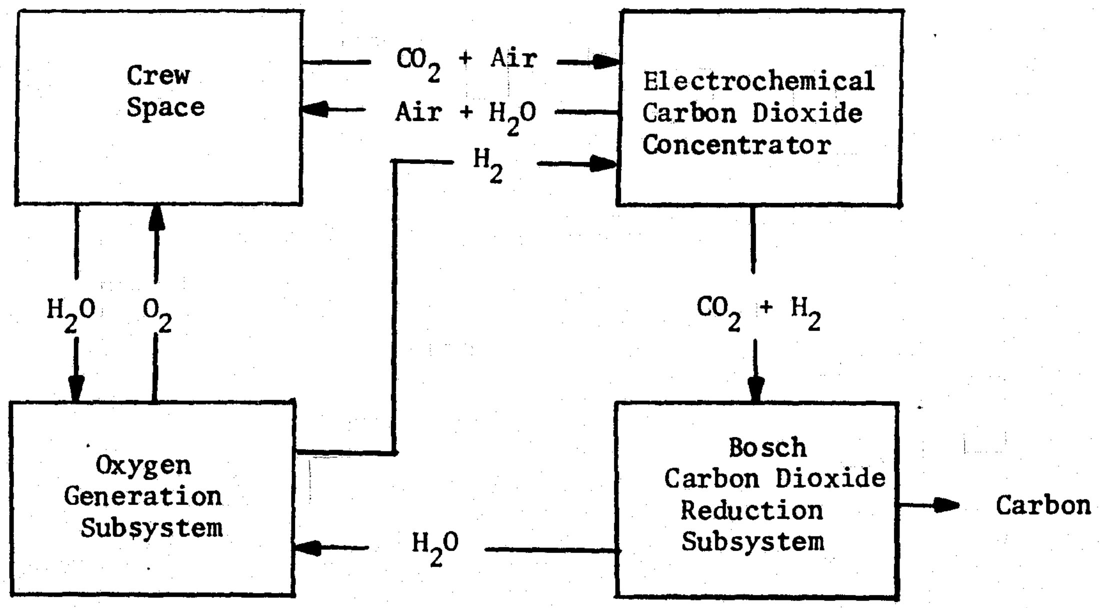


FIGURE 20 CLOSED OXYGEN LOOP WITH INTEGRATED EDC/B-CRS/OGS

TABLE 8 OPERATING CONDITOINS AND CHARACTERISTICS FOR THE EDC AS PART OF FOUR-PERSON LABORATORY BREADBOARD

Operating Time, h	901[a]
Number of Cells	45
Current Density, mA/cm^2 (ASF)	22.1 (20.5)
Current, A	5.00
pCO_2 Range, Pa (mm Hg)	306 to 466 (2.3 to 3.5)
Process Air Flow Rate, dm^3/min (cfm)	710 (25)
Process Air Temperature, K (F)	286 (56)
Process Air Dew Point, K (F)	284 (51)
CO_2 Removal Efficiency, %	73
Transfer Index	2.0
Average Cell Voltage, V	0.34
Power Generated, W	77
Heat Generated, W	200

(a) Includes Familiarization, Integrated Checkout and Shakedown, Design Verification and Endurance Tests.

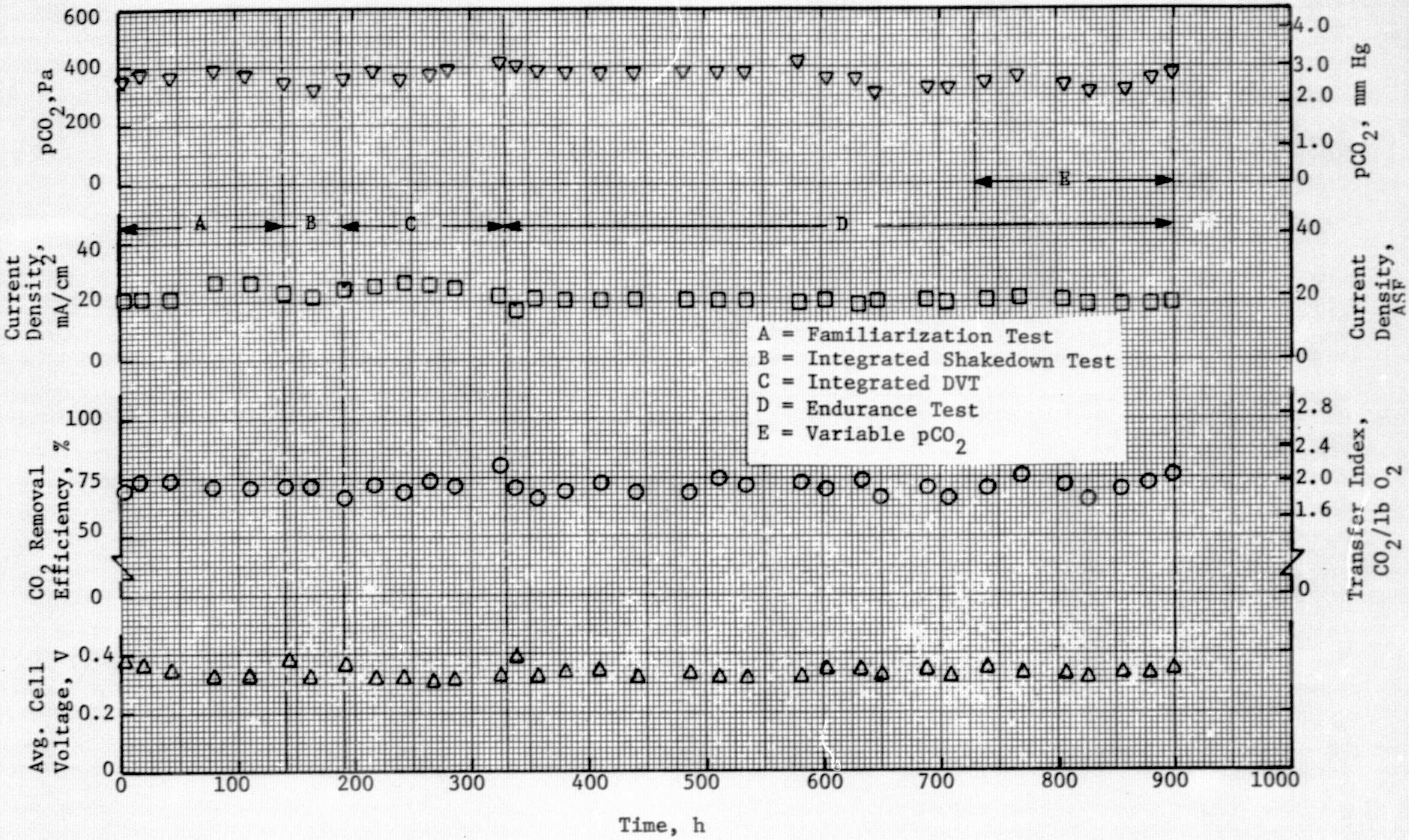


FIGURE 21 EDC PERFORMANCE DURING FOUR-PERSON INTEGRATED LABORATORY BREADBOARD TESTING

composition, and humidity conditions that are projected for a spacecraft cabin. The ASU is used to supply process and, if needed, cooling air to the EDC or ARX-1. A detailed description of the ASU was presented previously.(11) Presented herein is a summary of the test experience achieved with the ASU in support of the four-person laboratory breadboard tests discussed above.

Air Supply Unit Description

The principal mechanical components of the ASU are shown in Figure 22. Instrumentation is housed in a cabinet pictured in Figure 23. This cabinet includes the controls to operate the ASU blower, water pump and heater; the instrumentation and sensors to monitor and control temperature, pressure, humidity, CO_2 and O_2 levels and the capability to periodically calibrate the instruments. In addition, shutdown capability, both within the ASU and to and from other subsystems exists.

Test Results

Table 9 lists the operating conditions for the ASU during the four-person laboratory breadboard tests. Figure 24 shows the performance of the ASU over the 900 hours of testing. The ASU performed its function well throughout this testing.

SUPPORTING TECHNOLOGY STUDIES

Four studies were completed as part of this continuing effort. The four areas of investigation were: (1) development of an alternate anode current collector design, (2) definition of the optimum EDC current density for power sharing, (3) demonstration of EDC performance improvements at the single cell level and (4) testing with electrolyte mixtures to enhance EDC humidity tolerance.

Alternate Anode Current Collector Design

A development effort was conducted to select an alternate technique to apply the anode current collector to advanced EDC cell frames. The objective of this study was to identify and demonstrate techniques that would prevent polysulfone crazing, occasionally observed after extended times (greater than one year) with the presently used plating process. The baseline design incorporated plating of the anode current collector directly onto the polysulfone cell frame. This process consisted of a series of steps including electroless nickel plating followed by silver and gold plating. Besides the crazing, the unit cost per frame was also high.

Three alternate techniques for applying anode current collectors to the cell frames were investigated. One, called ion deposition plating, was evaluated and was found to be inadequate due to the brittleness of the resulting plating. A second plating technique, called plasma deposition, was found to be unacceptable due to difficulty in achieving the required thickness and uniformity.

The third technique evaluated proved acceptable and is presently projected for the fabrication of future EDC cells. The design uses thin silver metal foil, sized for the required current conduction, inserted into the anode cavity of

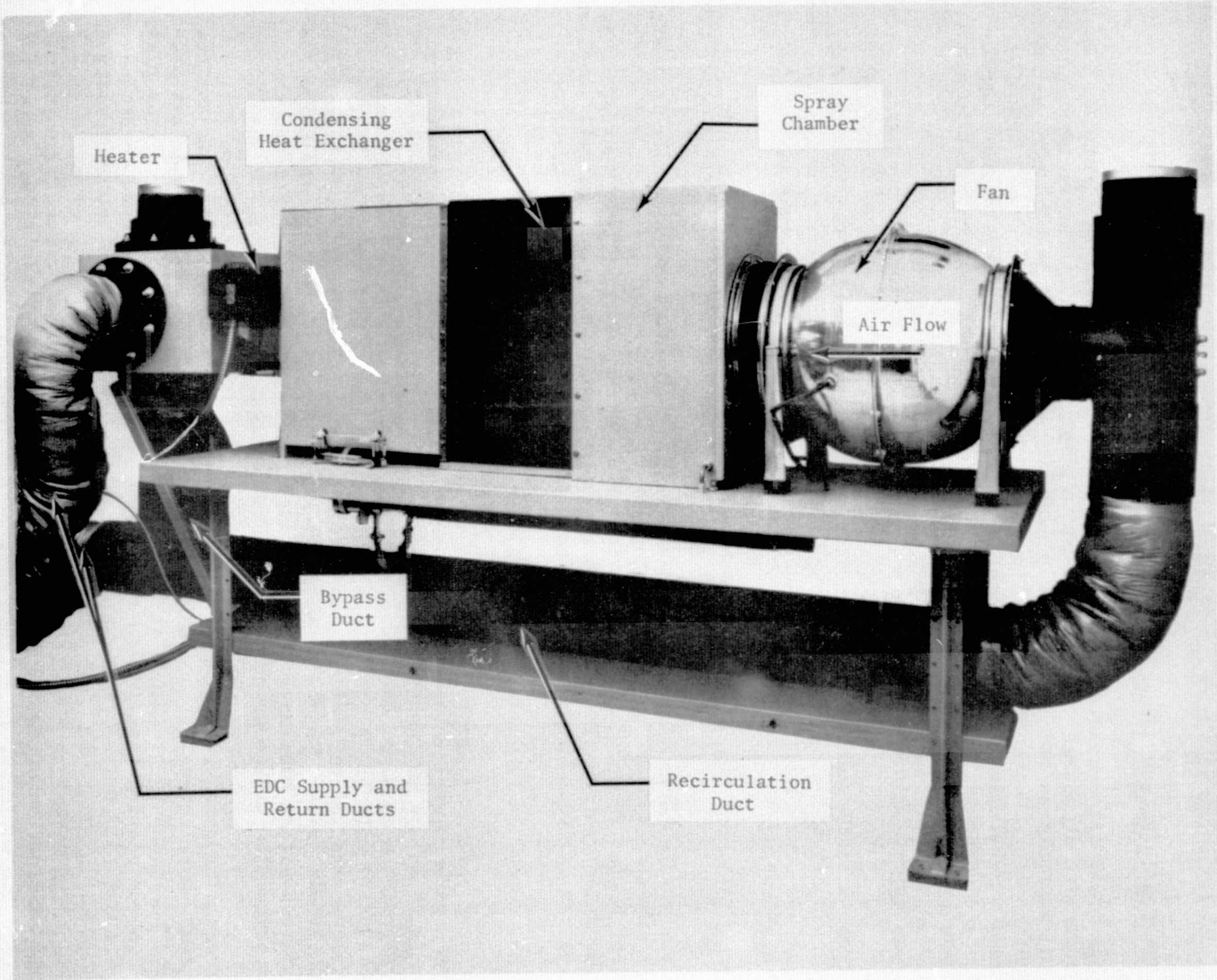


FIGURE 22 AIR SUPPLY UNIT

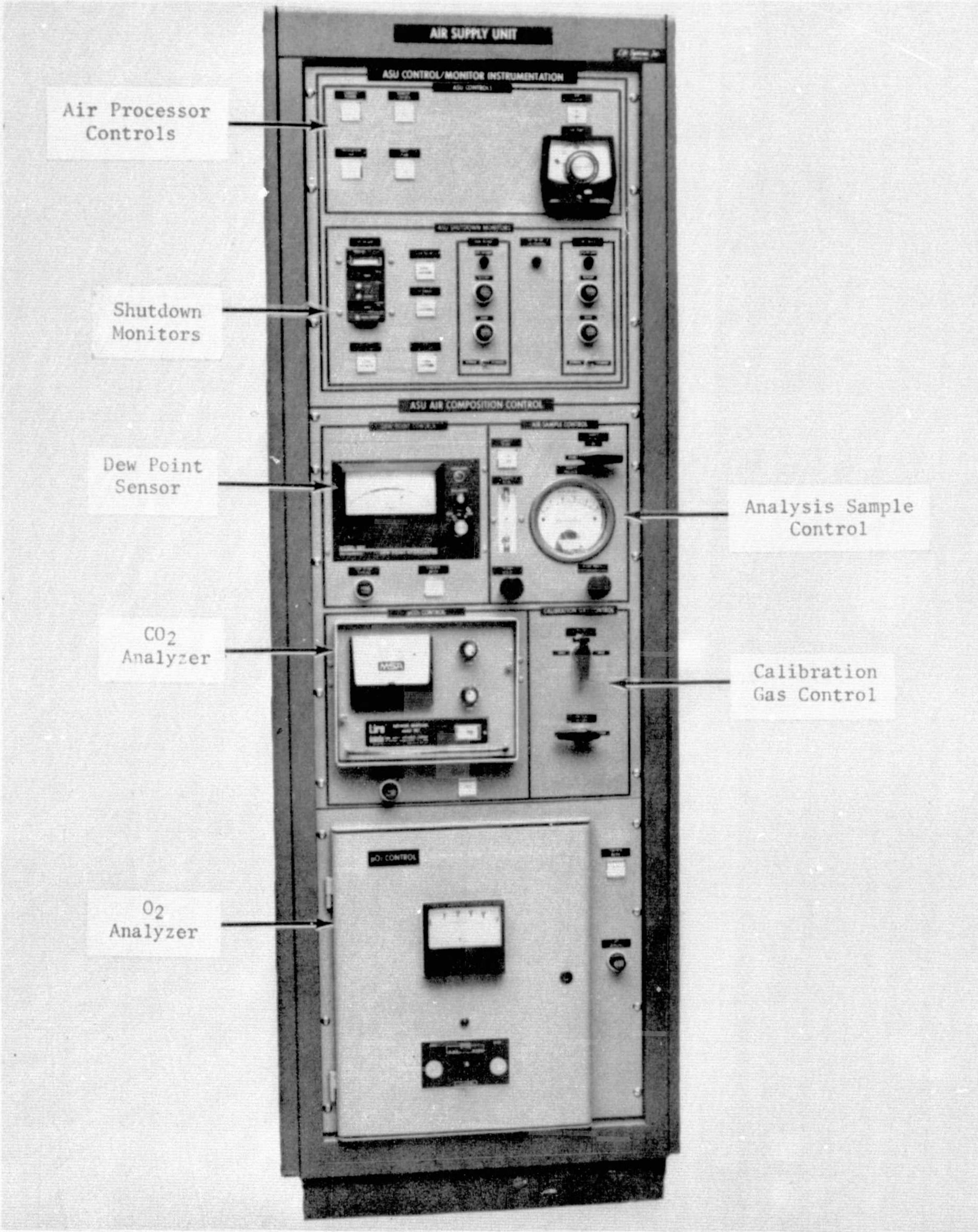


FIGURE 23 ASU CONTROL AND MONITOR INSTRUMENTATION CABINET

TABLE 9 ASU OPERATING CONDITIONS FOR FOUR-PERSON LABORATORY BREADBOARD TEST

Flow Rate to EDC, dm^3/min (cfm)	700 to 1020 (25 to 36)
Temperature, K (F)	286 to 290 (55 to 63)
Dew Point Temperature, K (F)	281 to 289 (47 to 60)
Relative Humidity, %	57 to 85
Pressure, kPa (psia)	101 ±0.74 (14.70 ±0.11)
Nominal Gas Composition, kPa (mm Hg)	
O_2	21.3 (160)
CO_2	0.40 (3.0)
N_2	Makeup

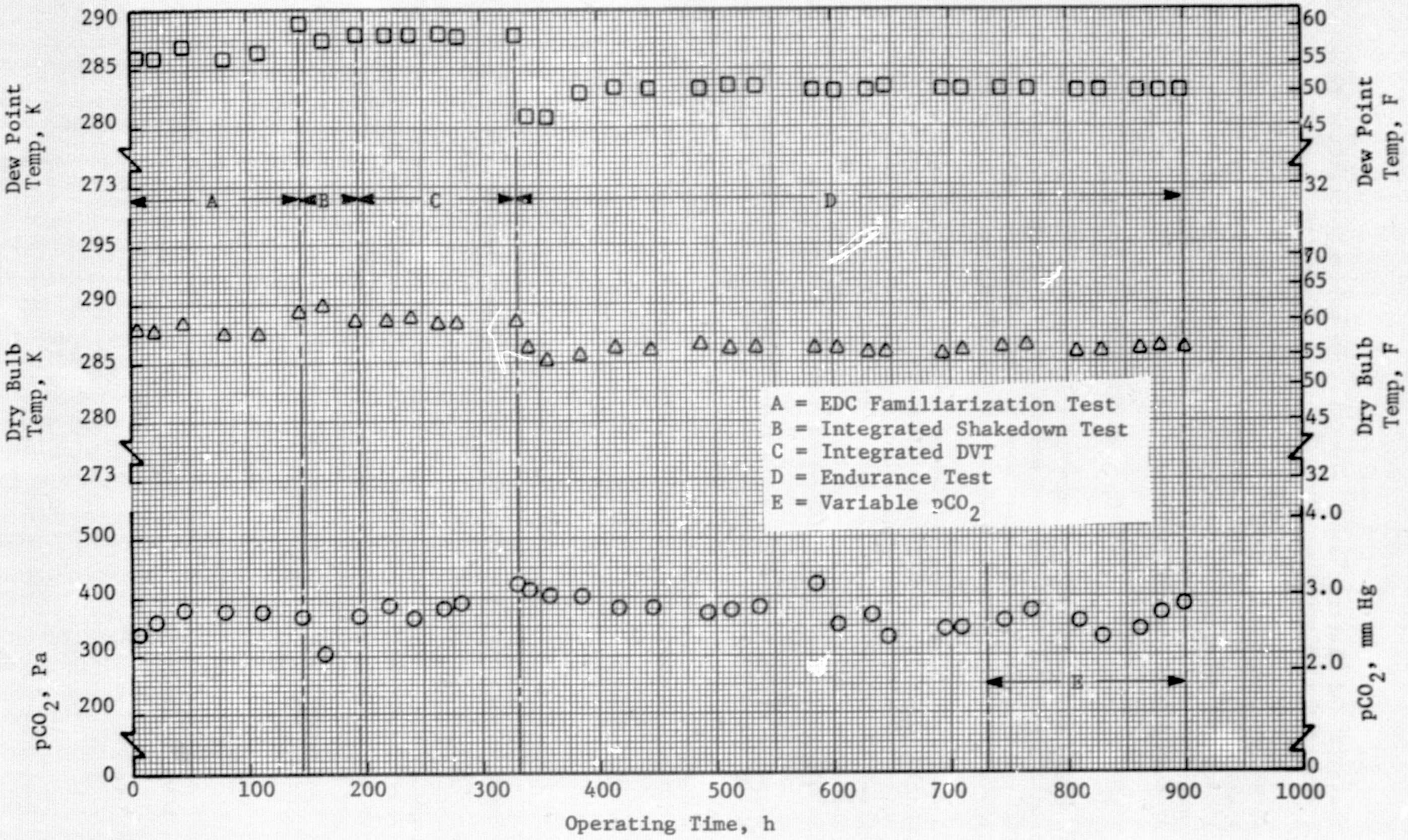


FIGURE 24 ASU PERFORMANCE DURING FOUR-PERSON INTEGRATED LABORATORY BREADBOARD TESTING

the cell and electron-beam welded to the current collector tabs. Modifications to the polysulfone frame have been completed to accept the metal foil.

Electrical resistance checks were made from the external tabs to the internal silver foil. A reduction of one order of magnitude in internal resistance losses was obtained compared to the plated design. Also, while materials costs are similar (same amount of silver used) the electron-beam welding process is substantially lower than plating.

Optimum EDC Current Density

A study was conducted to determine the optimum EDC current density that results in lowest total equivalent weight for spacecraft application when the EDC is used as a power generator as well as a CO_2 remover. The Advanced EDC (AEDC) hardware characteristics were used as the EDC model for the study.[10]

A computer program was written to facilitate calculation of total equivalent weight based on given input parameters. The equivalent weight was determined from several factors. These included CO_2 removal rate or capacity which relates to fixed hardware weight. Also, weight penalties incurred because of the power used, heat rejected and the O_2 consumed by the EDC were included. An equivalent weight credit was given for the power produced by the EDC.

Computer results of total equivalent weight versus current density curves for 1, 3, 6 and 12-person EDCs are shown in Figure 25. In these and other test cases, the optimum current density for the lowest total equivalent weight occurred slightly below the current density that maximized CO_2 removal efficiency. Using the EDC generated power in other electrochemical subsystems of an ARS reduces overall power, but has only a small impact on optimum EDC current density. In general, a slightly lower current density that that for optimum CO_2 removal results.

"B Level" Technology Study

This program activity was directed toward the testing and analysis of Contractor-generated hardware concepts which promised improvements in performance. Performance levels were selected as goals to judge and compare EDC cell operation. These performance levels were termed "B-level" performance goals. Previous EDC performance goals, termed "A-level," had been established prior to the development of the one-person and the six-person EDCs.[5,6,7] These goals were demonstrated and exceeded during these developments. Therefore, the establishment of "B-level" performance goals was required to further direct EDC technology advancement.

A comparison of "A-" and "B-level" performance as a function of inlet air pCO_2, operating current density and inlet air RH are presented in Figures 26, 27 and 28, respectively. The operating conditions for these comparisons are shown in Table 10.

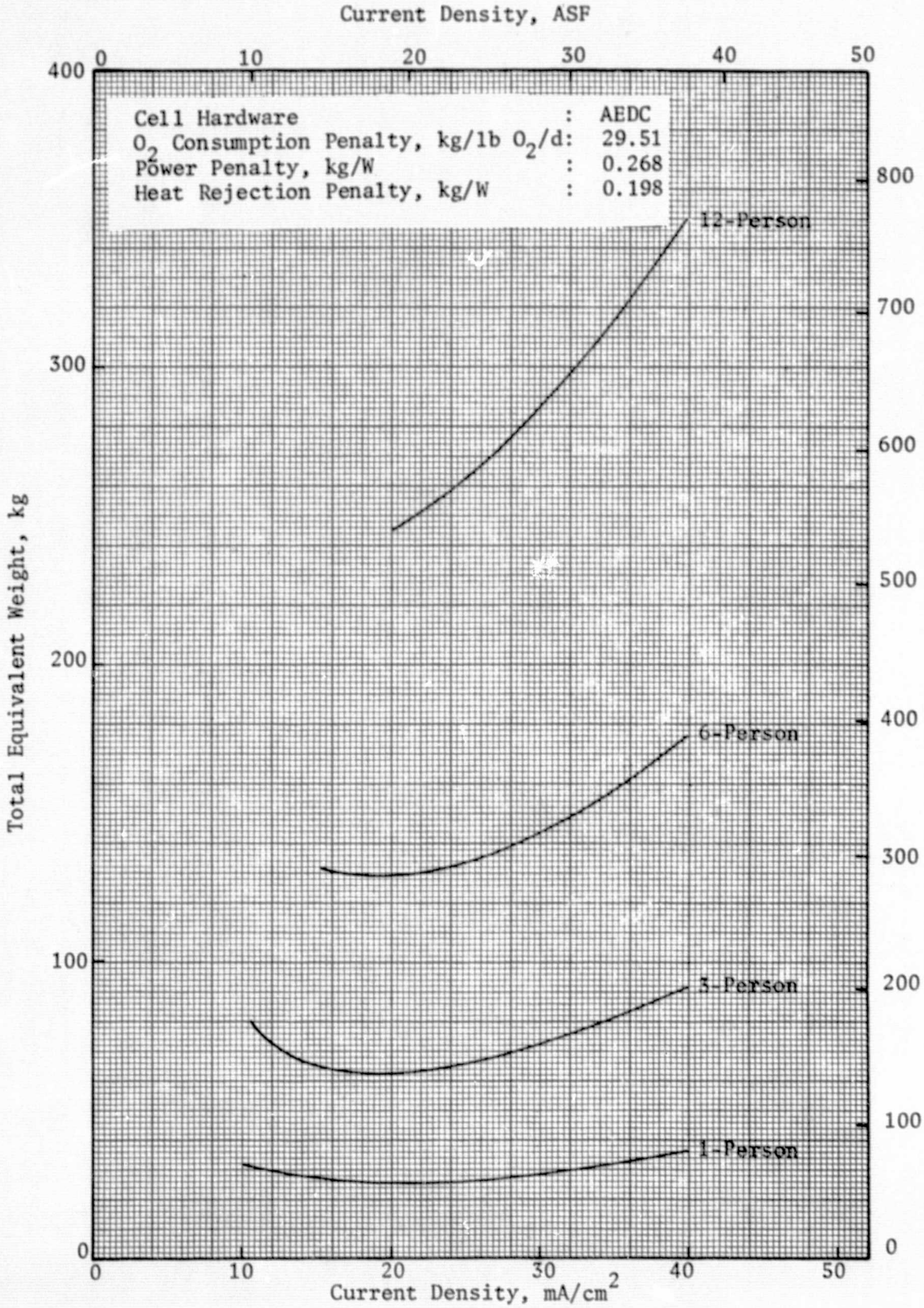


FIGURE 25 TOTAL EQUIVALENT WEIGHT AS A FUNCTION OF CURRENT DENSITY

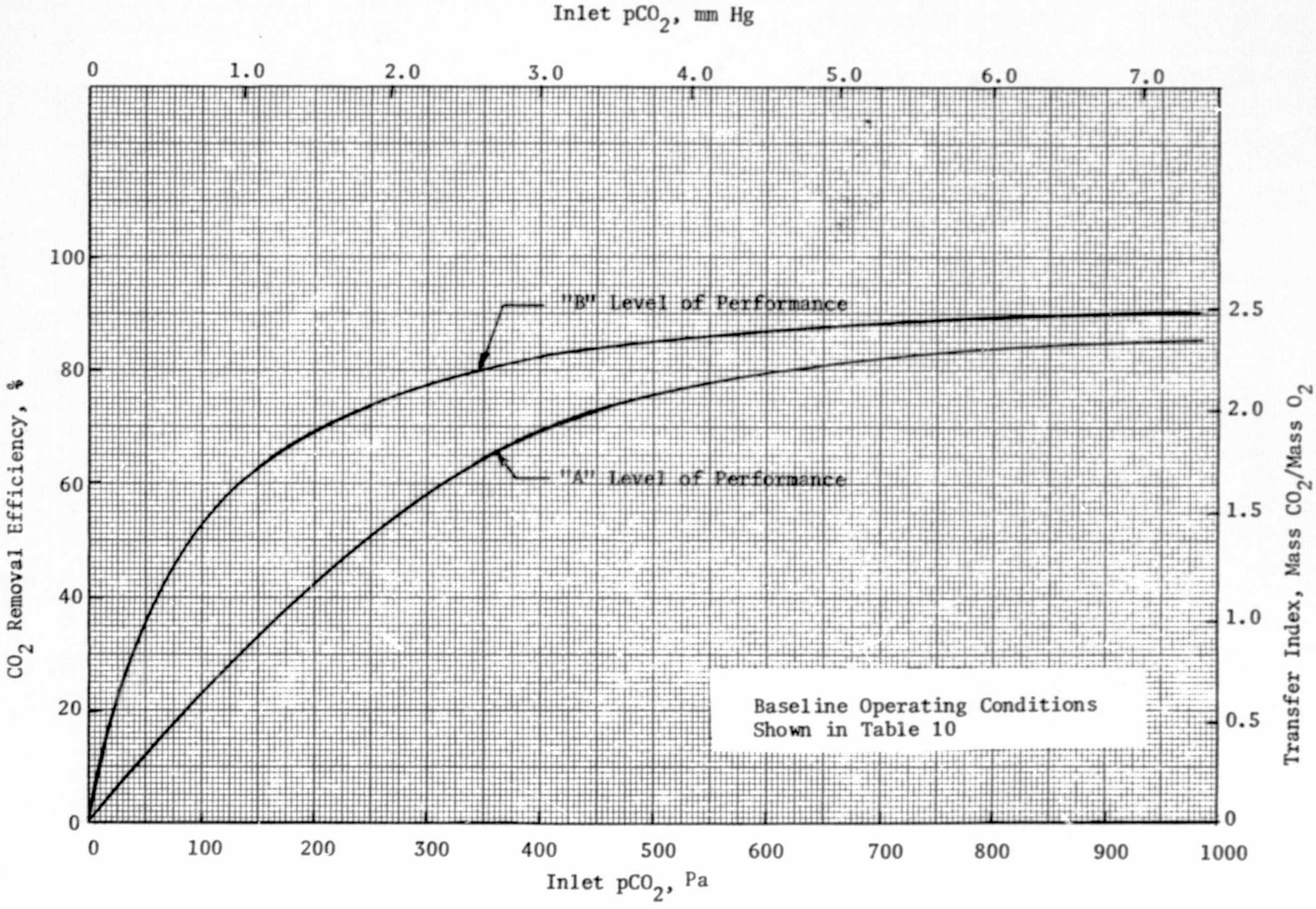


FIGURE 26 COMPARISON OF "A" AND "B" LEVEL OF EDC PERFORMANCE GOALS (INLET pCO_2)

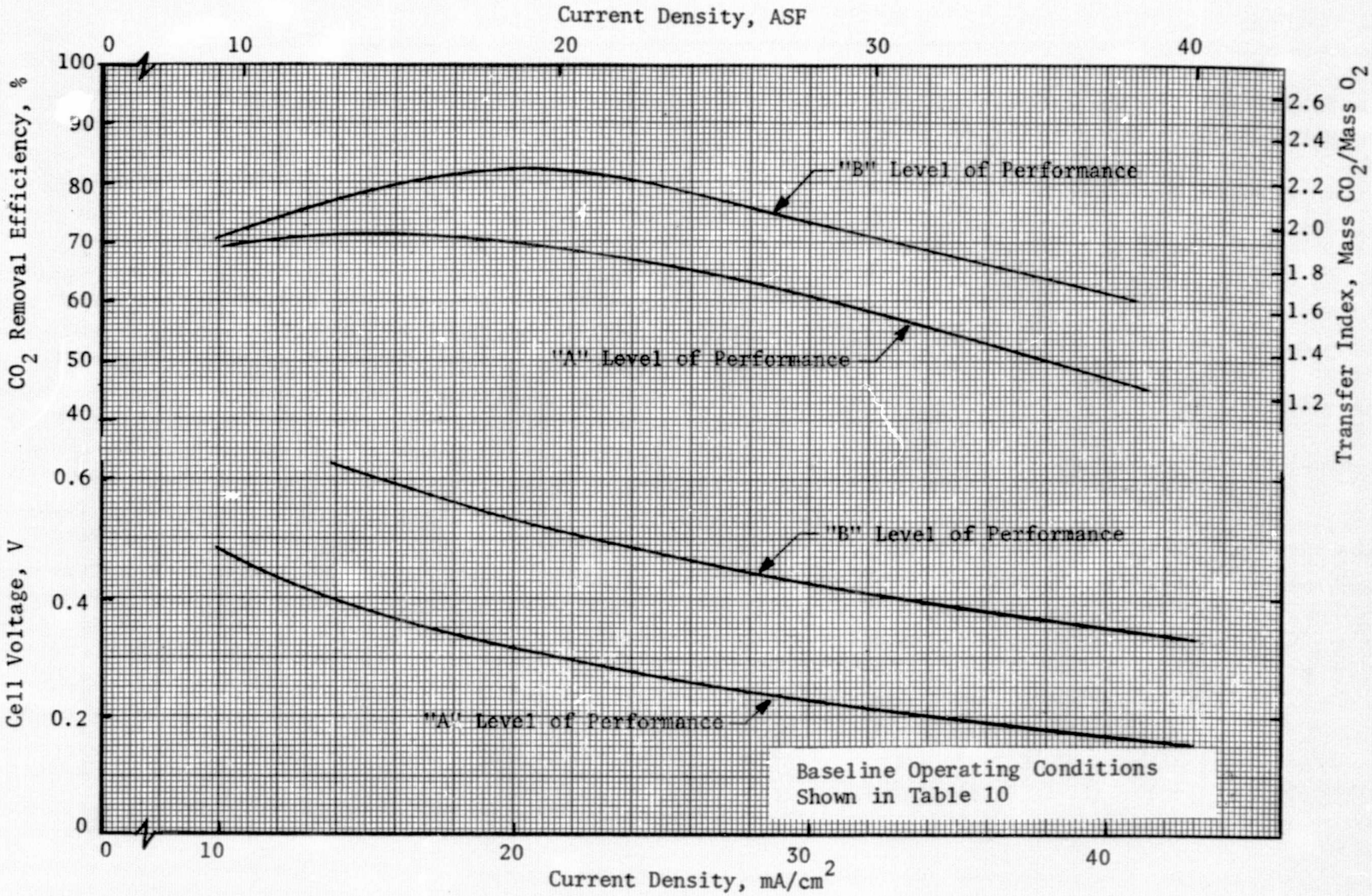


FIGURE 27 COMPARISON OF "A" AND "B" LEVEL OF EDC PERFORMANCE GOALS (CURRENT DENSITY)

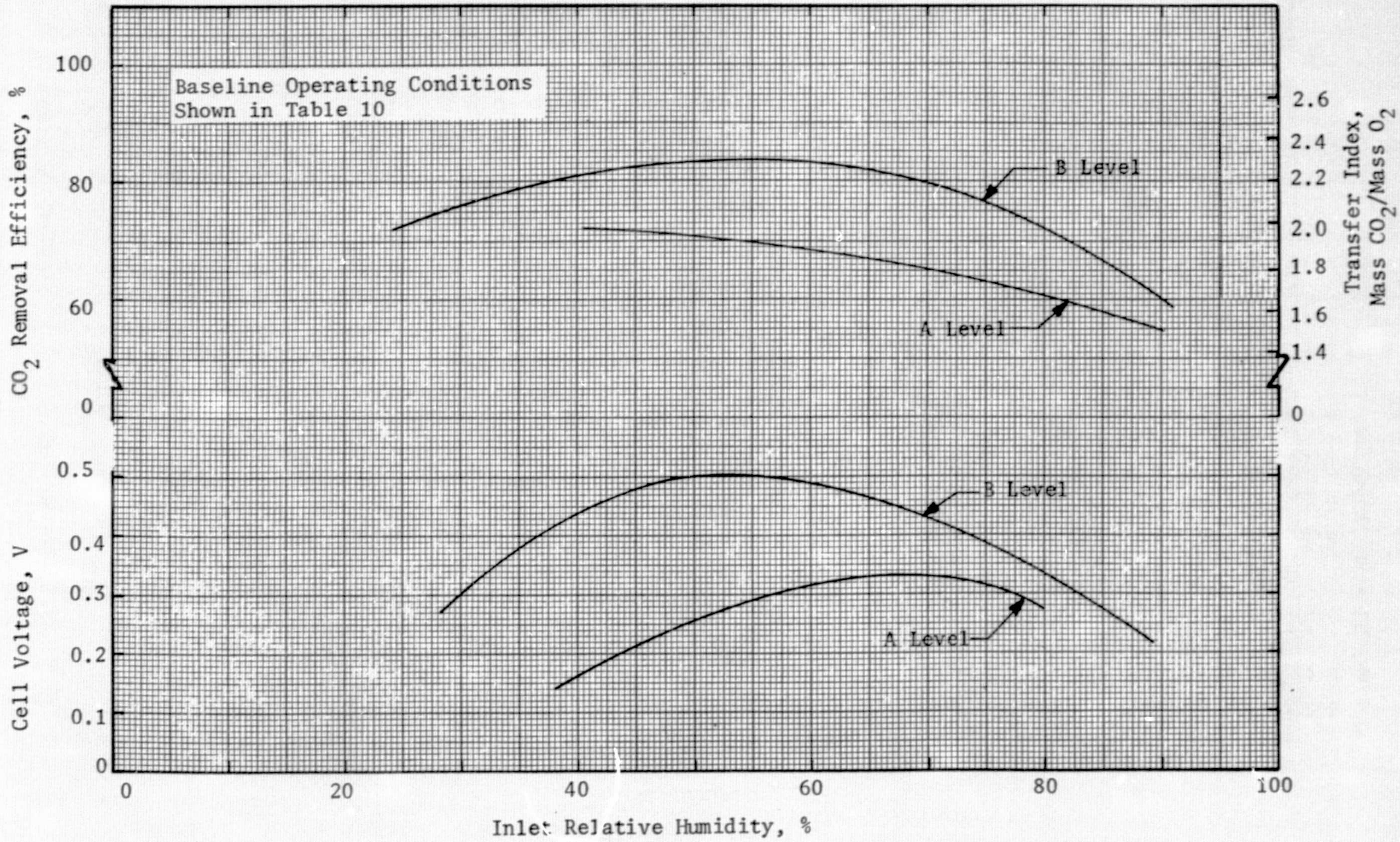


FIGURE 28 COMPARISON OF "A" AND "B" LEVEL OF EDC PERFORMANCE GOALS (RELATIVE HUMIDITY)

TABLE 10 BASELINE OPERATING CONDITIONS FOR "A" AND "B" PERFORMANCE LEVEL COMPARISONS

pCO_2, Pa (mm Hg)	400 (3.0)[a]
Current Density, mA/cm^2 (ASF)	21.5 (20)[b]
Air Flow/Cell,[c] dm^3/s (scfm)	0.75 (1.60)
Inlet Process Air Temperature, K (F)	294 ±3 (70 ±5)
Inlet RH, %	
"A" Level	40 to 80
"B" Level	20 to 90
$H_2 + CO_2$ Backpressure	Ambient

(a) Variable for Figure 26
(b) Variable for Figure 27
(c) For a 0.045 m^2 (0.488 ft^2) active cell area

Study Approach

The testing to demonstrate "B-level" technology was divided into two major phases. In each phase four EDC hardware configurations or concepts were evaluated. Three levels of testing, consisting of checkout/acceptance, parametric and endurance testing were conducted. The checkout/acceptance test screened the performance of each of the four concepts. Up to three were selected for further parametric testing to determine the effects of the inlet air pCO_2, current density and inlet air RH. With the completion of the parametric testing, one or two of the best candidates were selected for 60 days of endurance testing. The second phase repeats the evaluation process for four different concepts.

The first phase of the testing has been completed and is reported herein.

Concept Selection Approach

The cell hardware concepts tested during the "B-level" technology study were chosen from a list of Contractor-generated hardware configurations. The approach for the selection from this list of hardware concepts was based on three factors. The first factor was the ability of the EDC hardware concept to demonstrate the complete range of "B-level" performance goals. The second factor was the ability of the concept to improve operational reliability through increased cell voltage and increased tolerance to wide ranges in air RH. The last factor was the potential of the concept to perform better in any single one of the performance characterization areas (e.g., cell voltage, CO_2 removal efficiency) the "B-level" performance goals established.

Table 11 is a list of the initial four concepts selected for the "B-level" technology study. This table also defines the basic cell hardware stackup, the type of electrochemical cell hardware utilized and the primary reason for the selection of the concept.

Test Results and Analysis

The four concepts selected and listed in Table 11 were evaluated according to the approach defined above.

High Moisture Tolerance Cell Design - The initial checkout testing of the high moisture tolerance cell demonstrated sufficiently high performance levels to be accepted for parametric testing. The baseline operating conditions selected for all tests for this concept are defined in Table 12. The parametric test results of this cell design are shown in Figures 29 through 32. The dashed lines in each figure represent the "B-level" technology goals established for EDC performance.

The performance of the high moisture tolerance cell design as a function of inlet pCO_2 matched, within experimental error, the design goal, as indicated in Figure 29. A shift in the peak of the performance curve as a function of current density for the high moisture tolerance design is indicated in Figure 30. The maximum removal efficiency of 85% occurred at a current density of 26.9 mA/cm^2 (25 ASF) compared to the "B-level" goal of 82% at a cur-

TABLE 11 CELL CONCEPTS FOR "B-LEVEL" TECHNOLOGY TESTS

Cell Design Concept No.	Concept Description	Stack-up Designation (Cathode/ Matrix/Anode)	Cell Hardware	Primary Reason for Selection
1	High Moisture Tolerance Design	10/20/30	AEDC[a]	Demonstrate all "B-level" performance goals
2	E-10 EDC Design	10/20/30	CS-6[b]	Demonstrate "B-level" performance with special emphasis on exceeding voltage goal
3	Internal Electrolyte Reservoir Design	10/20/10	AEDC[a]	Demonstrate "B-level" performance over widest range possible in inlet air relative humidity
4	Secondary Electrode Design	10/30/10	CS-6[c]	Demonstrate concept for altering the water concentration of an operating EDC with less dependancy on inlet parameters

(a) One-half square foot advanced, lightweight cell hardware, internally air-cooled.
(b) One-quarter square foot cell hardware as used for Six-Person Space Station Prototype (SSP) CO_2 Concentrator Subsystem, but internally air-cooled.[7]
(c) One-quarter square foot cell hardware as used for six-person SSP CO_2 Concentrator Subsystem. externally air-cooled fins.[7]

TABLE 12 HIGH MOISTURE TOLERANCE CELL
BASELINE OPERATING CONDITIONS

Number of Cells	1
Current, A	9.76
Active Surface Area, cm^2 (ft^2)	453 (0.488)
Electrolyte	LSI-D
Temperature, K (F)	299 ±1.6 (78 ±3)
Air Inlet Dew Point, K (F)	285 ±2.2 (54 ±4)
Air Pressure	Ambient
Air Inlet pCO_2, Pa (mm Hg)	400 (3.0)
Air Flow Rate, dm^3/s (scfm)	0.94 (2.0)
H_2 Flow Rate, dm^3/s (slpm)	3.3×10^{-3} (0.20)

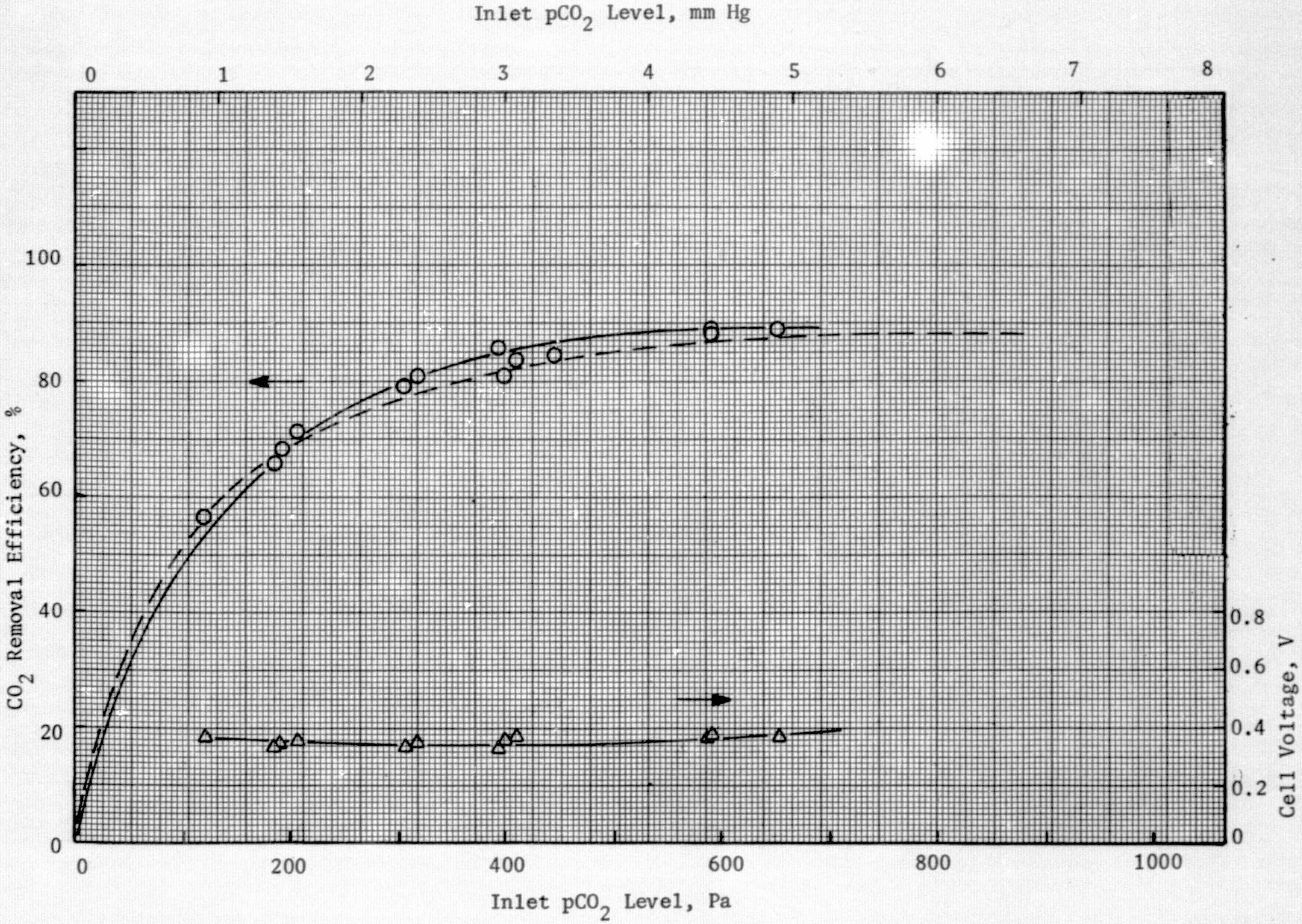


FIGURE 29 HIGH MOISTURE TOLERANCE CELL, INLET pCO_2 PERFORMANCE

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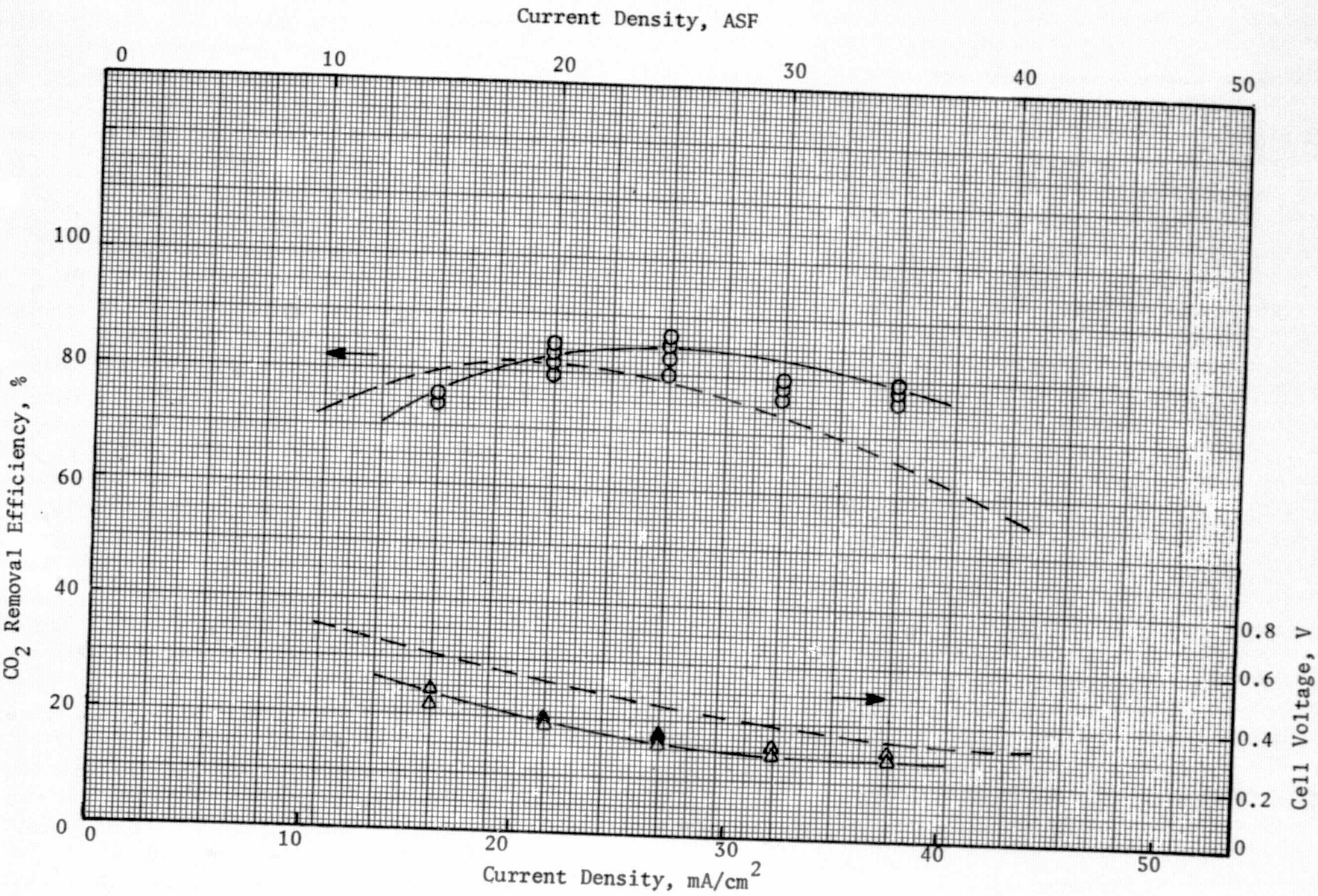

FIGURE 30 HIGH MOISTURE TOLERANCE CELL, CURRENT DENSITY PERFORMANCE

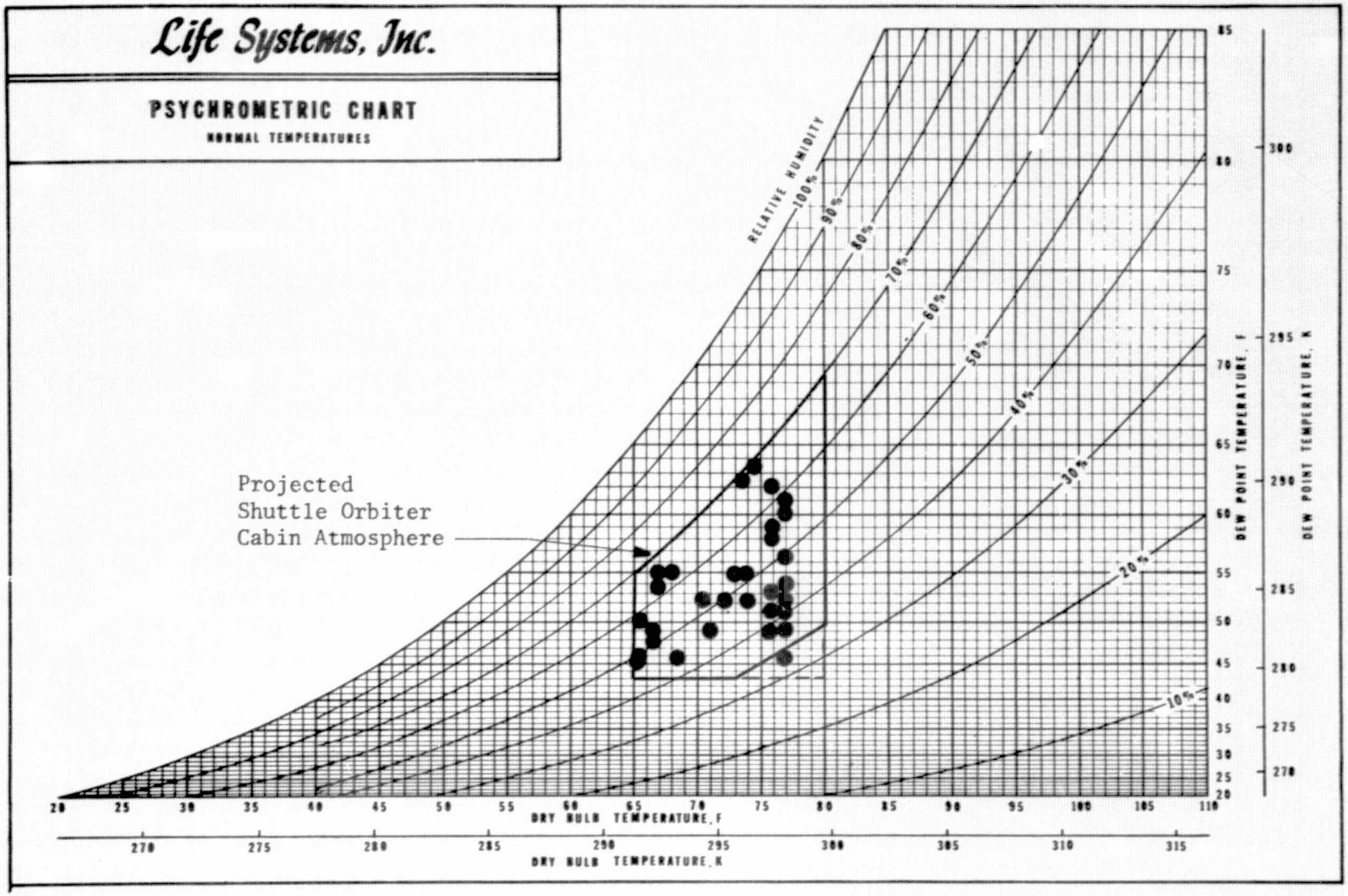

FIGURE 31 HIGH MOISTURE TOLERANCE CELL, AIR HUMIDITY PERFORMANCE

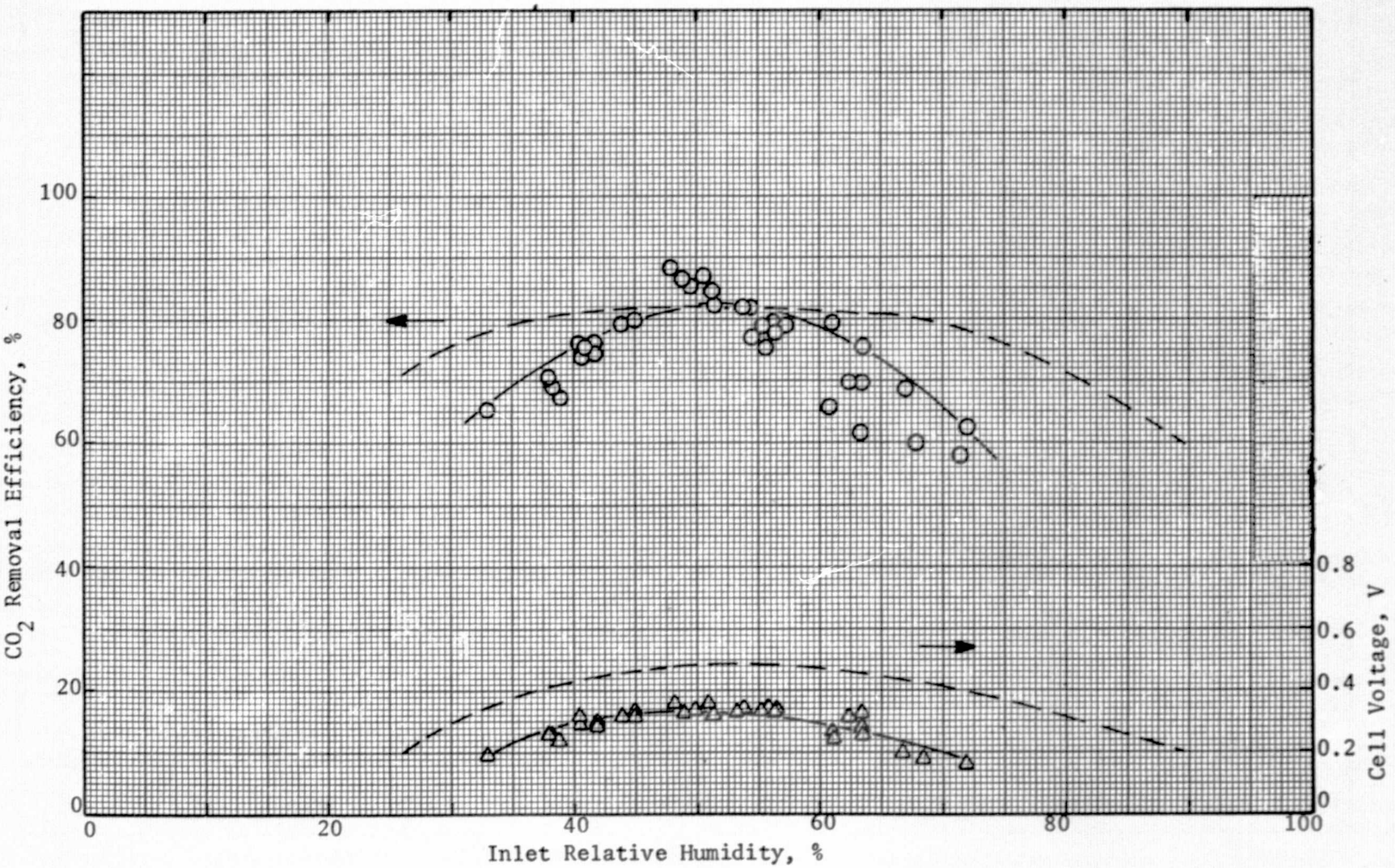

FIGURE 32 HIGH MOISTURE TOLERANCE CELL, INLET RELATIVE HUMIDITY PERFORMANCE

of 20.4 mA/cm^2 (19 ASF). Electrical performance of the cell was approximately 0.1 V below the goal.

The high moisture tolerance cell was operated over a wide range of inlet RH conditions as illustrated in Figure 31. The cell performance as a function of inlet air RH is shown in Figure 32. The cell showed excellent operating tolerance over a range of 33 to 72% inlet air RH. The characteristically curved shape of performance versus RH was again observed, with decreases in performance both at high and low RH ranges. For the cell tested over the indicated range in RH, the CO_2 removal performance varied from 60 to 85%. The peak CO_2 removal efficiency occurred at an inlet RH level of 52%. Cell voltage was again lower as desired.

Based on the results of the parametric testing, the high moisture tolerance cell was selected for endurance testing. The cell was successfully operated for 75 days.

E-10 EDC Cell Design - The E-10 EDC is similar to the Contractor's high moisture tolerance cell design except the baseline cathode is exchanged for an E-10 type electrode. This electrode has a modified catalyst composition which was previously demonstrated as an efficient O_2 evolution electrode. The potential for increasing EDC operating voltages was projected using this electrode as the cathode of an EDC. However, during the initial checkout testing, the E-10 EDC showed very high voltages (>0.5 V) but failed to maintain positive voltage operation after 24 hours and the testing was discontinued.

Internal Electrolyte Reservoir Cell Design - The initial checkout testing of the internal electrolyte reservoir cell design was performed at the baseline conditions defined in Table 13. The results of the checkout testing demonstrated promising performance and hence acceptance for parametric testing. The results of the parametric characterizations are shown in Figures 33 through 36.

Carbon dioxide removal efficiency of the internal electrolyte reservoir cell as a function of inlet pCO_2 is shown in Figure 33. As shown, "B-level" technology performance above an inlet pCO_2 level of 400 Pa (3 mm Hg) was obtained. At lower pCO_2 levels, the cell performance was slightly below the established technology goal. As shown in Figure 34, no peak in CO_2 removal efficiency was observed as a function of current density over the range tested. As indicated, performance was steadily increasing with decreasing current density level and exceeded the goal above 19.4 mA/cm^2 (18 ASF). Above that current density, the performance was slightly less than the performance goals established. The range of inlet RH over which the electrolyte reservoir cell was tested is defined in Figure 35 and the performance results are shown in Figure 36. The cell was successfully operated over a range of 33 to 65% RH. A performance peak was observed at an inlet RH level of 56% resulting in CO_2 removal efficiency of 80%. Voltage levels were generally less than the goals established.

While the internal electrolyte reservoir cell did not expand the operational tolerance to RH it demonstrated better performance levels, both CO_2 removal and cell voltage, as a function of air RH. Also, operation at lower absolute dew points and dry bulb temperatures still yielded good performance. Also, with an increased current density of 32.3 mA/cm^2 (30 ASF), versus a baseline of 21.5 mA/cm^2 (20 ASF), the cell successfully tolerated 28% RH.

TABLE 13 INTERNAL ELECTROLYTE RESERVOIR
CELL BASELINE OPERATING CONDITIONS

Number of Cells	1
Current, A	9.4
Active Surface Area, cm^2 (ft^2)	437.5 (0.470)
Electrolyte	LSI-D
Temperature, K (F)	299 ±1.5 (79 ±3)
Air Inlet Dew Point, K (F)	285 ±0.5 (54 ±1)
Air Pressure	Ambient
Air Inlet pCO_2, Pa (mm Hg)	400 (3.0)
Air Flow Rate, dm^3/s (scfm)	0.99 (2.1)
H_2 Flow Rate, dm^3/s (slpm)	3.7×10^{-3} (0.22)

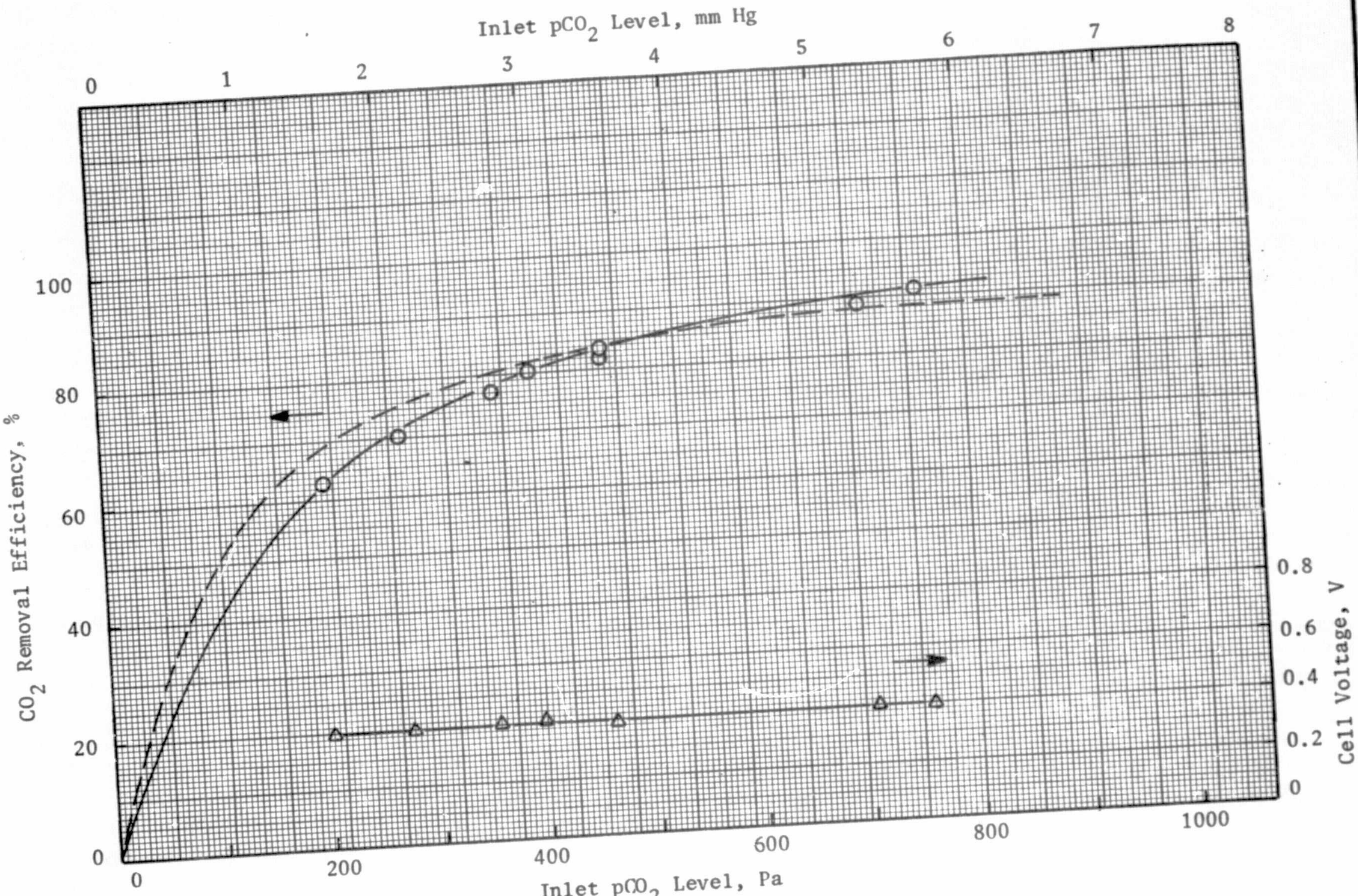

FIGURE 33 INTERNAL ELECTROLYTE RESERVOIR CELL, INLET pCO_2 PERFORMANCE

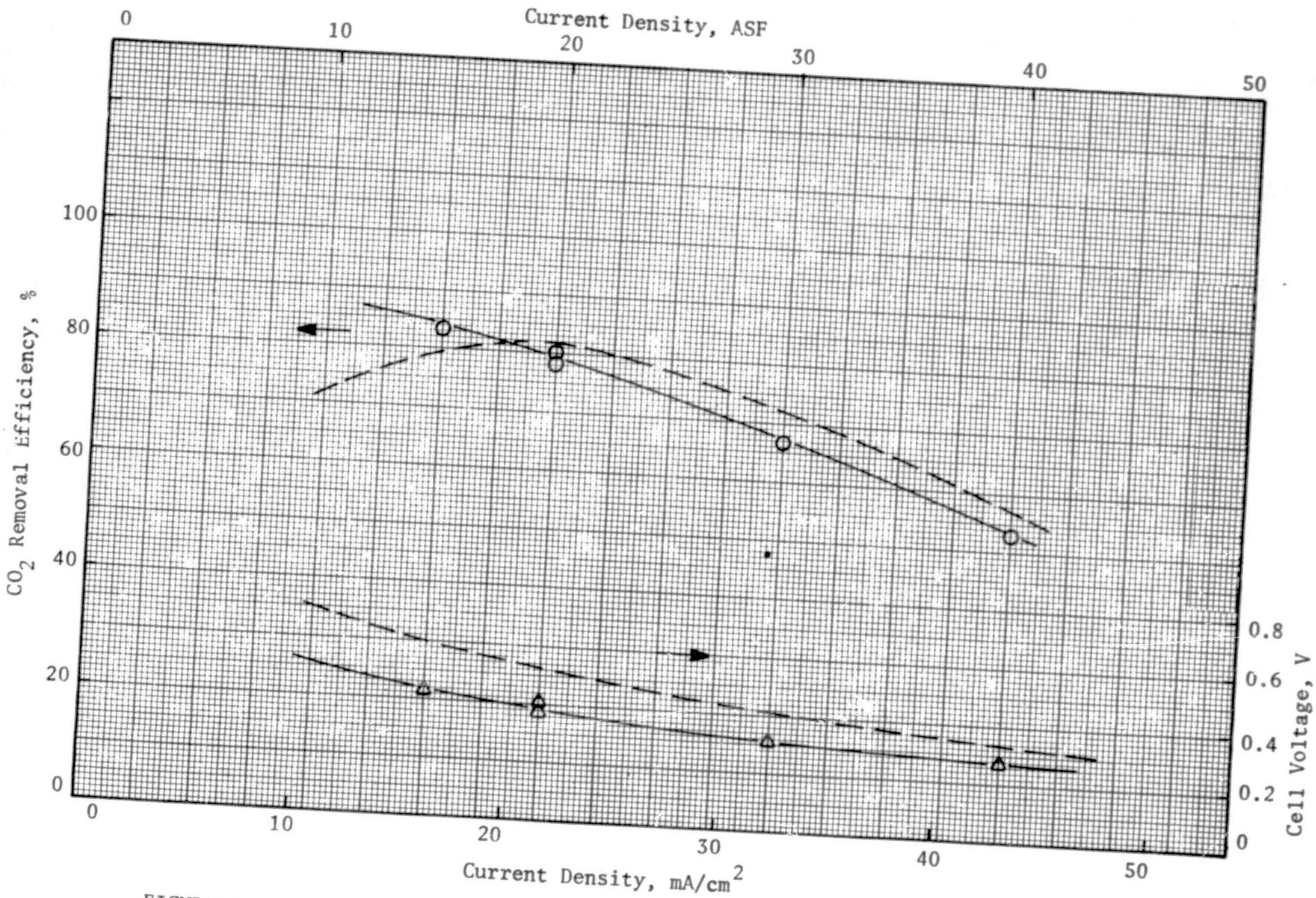

FIGURE 34 INTERNAL ELECTROLYTE RESERVOIR CELL, CURRENT DENSITY PERFORMANCE

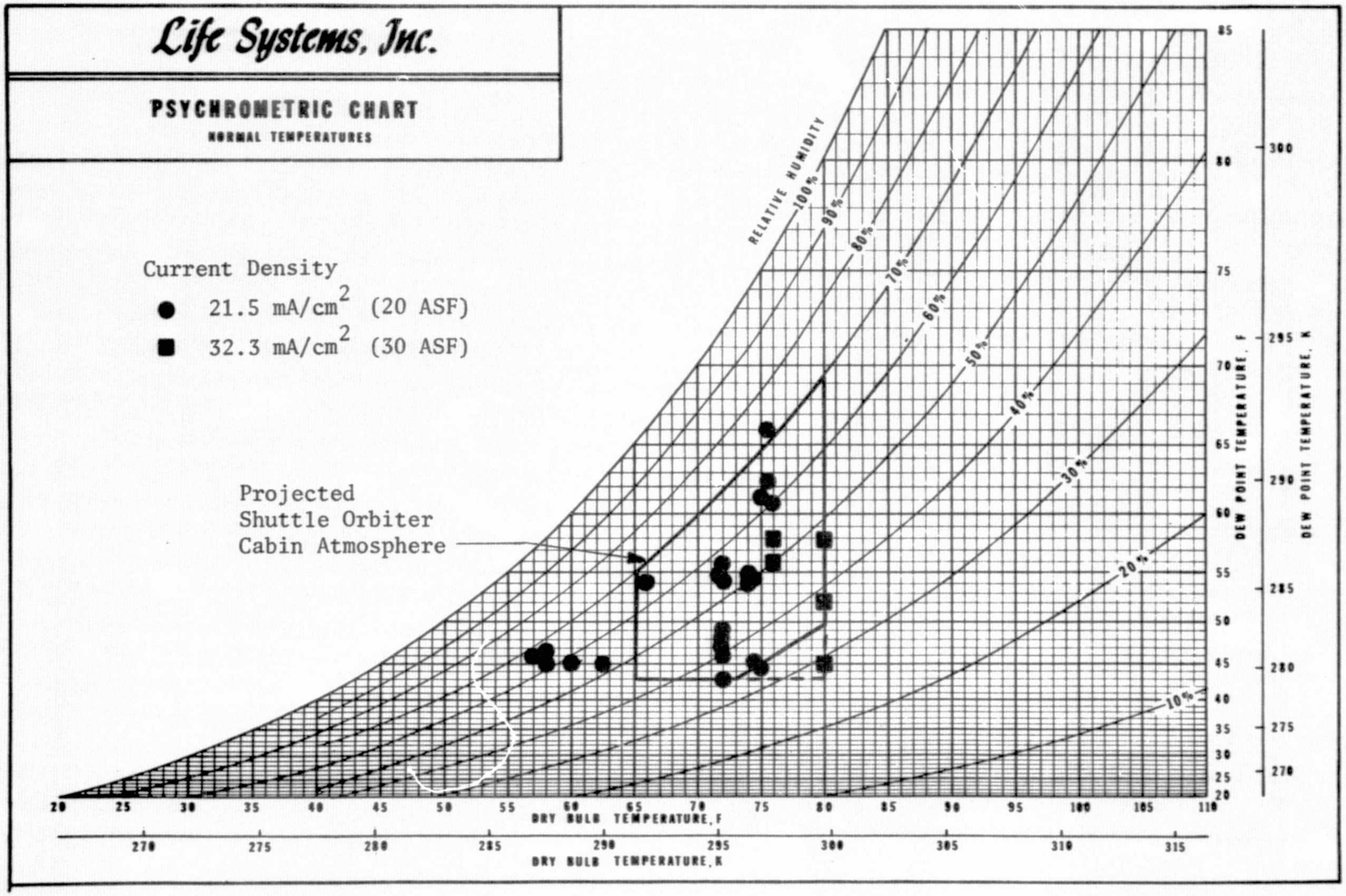

FIGURE 35 INTERNAL ELECTROLYTE RESERVOIR CELL, AIR HUMIDITY PERFORMANCE

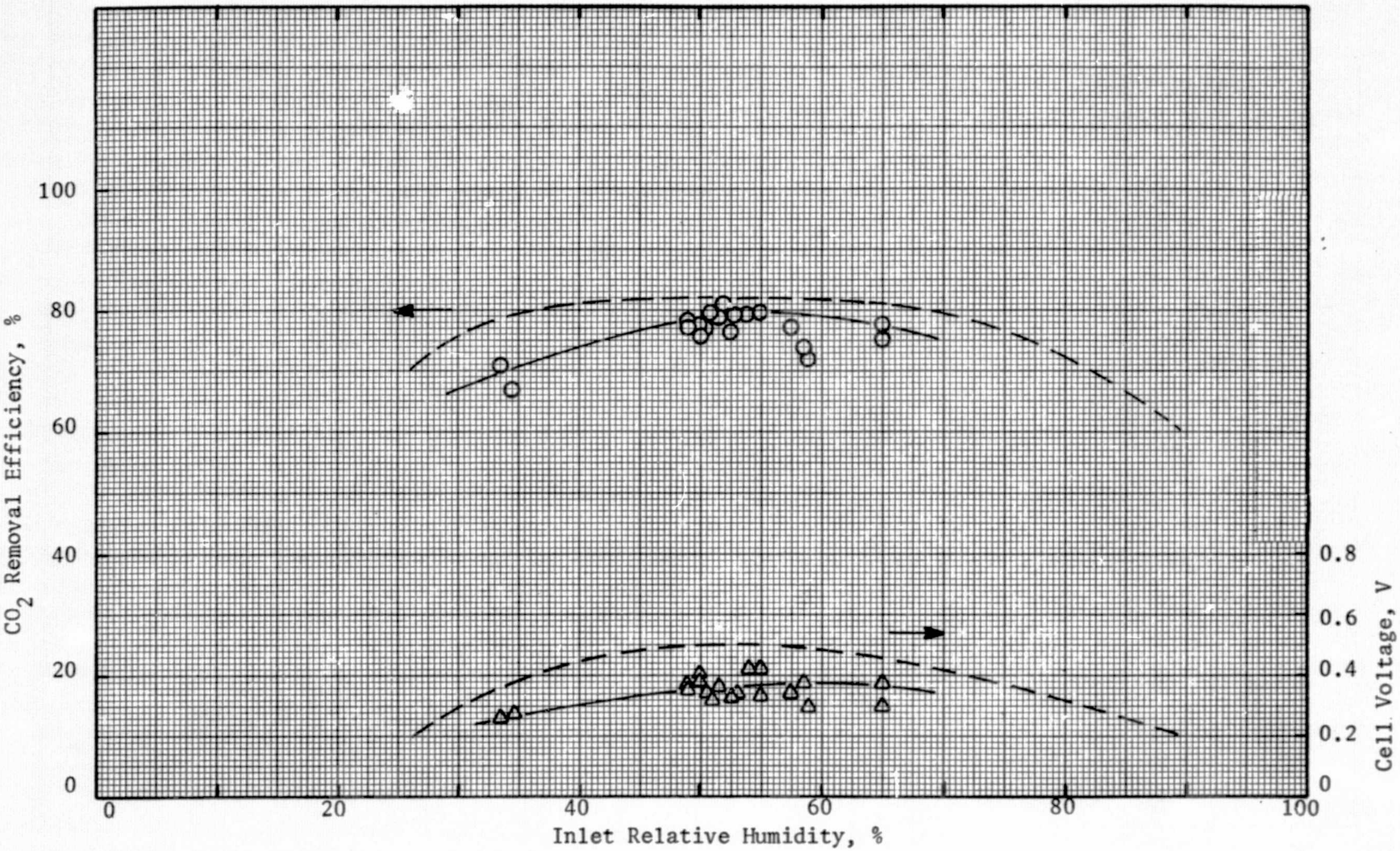

FIGURE 36   INTERNAL ELECTROLYTE RESERVOIR CELL, INLET RELATIVE HUMIDITY PERFORMANCE

Based on the "B-level" of performance demonstrated by the electrolyte reservoir cell during the parametric testing the cell was selected for endurance testing. The cell was successfully tested for 67 days.

Membrane Electrode Cell Design - The fourth cell design projected to demonstrate "B-level" performance was the membrane electrode design. This concept was projected as a method for altering the moisture content of an operational EDC without changing the inlet air RH condition.

During the initial screening tests, the membrane electrode concept demonstrated two major effects on EDC cell performance. First, the projected change in moisture content, hence potentially wide RH tolerance, was demonstrated. Second, an increase in CO_2 removal performance was observed. For example, a 20% increase in CO_2 removal efficiency from 75 to 90% was demonstrated. The cell, however, showed voltage stability problems and further analysis and testing is required to fully characterize the potential of this concept.

Electrolyte Mixture Study

To expand the capability of EDCs to operate efficiently at the low process air RHs encountered in spacecraft atmospheres (as low as 26% RH), electrolytes composed of mixtures of carbonate salts were studied. The premise for the study was that two dissimilar salts can produce concentrated solutions of greater ionic solubility than the concentrated solution of either single salt. This increased ionic solubility will maintain an increased ionic water binding force which results in decreasing the water vapor pressure (pH_2O) of the solution. For EDC electrolytes it is necessary to consider the dew point depression characteristics of both the carbonate ($CO_3^{=}$) and bicarbonate (HCO_3^{-}) forms of the electrolyte mixture since both species are present in an operating EDC cell.

Mixture Selection Techniques

Since it is desirable to operate EDCs at low process air RHs, electrolytes which exhibit a high dew point depression are desired. The electrolytes must still be carbonates to satisfy the basic EDC requirements. For the purpose of this study the salts of the alkali metal family were considered.

Both analytical and experimental evaluations of potential mixtures of the salts were used to attempt to predict potentially-promising ratios. Initially, potential mixtures were evaluated for optimum solubility based on the activity coefficients of the independent salt concentrations in the solution. The dew point depression characteristics of several of these mixtures were then experimentally determined. Correlation between analytical prediction and experimental results were difficult to establish and were inconclusive. Dew point depression test results indicated that an equilibrium with 25% RH air was possible, however, practical EDC cell operation would be substantially more limited due to operational gradients and mass transport limits. Full-sized cell testing was therefore selected for final determinations.

Single Cell Testing

A test program was performed in an attempt to predict electrolyte mixture effects on EDC operation. The objectives of the test were to quantify possible effects of the electrolyte mixtures on the CO_2 removal and electrical efficiencies of an EDC cell as a function of inlet air pCO_2 level, current density and inlet RH. The electrolyte mixture with the potentially highest dew point depression was selected. A single cell EDC was assembled utilizing the CS-6 type hardware (that developed for the six-person EDC for the SSP application[7]) and charged with the electrolyte. The charge concentration was adjusted to an ionic concentration equivalent to the baseline EDC 62.5% cesium carbonate (Cs_2CO_3) charge solution.

The test results illustrated only baseline performance, indicating that the overall effects of mixed electrolytes on performance are negligible within the baseline operating ranges of an EDC.

CONCLUSIONS

The following conclusions are a direct result of the program activities:

1. The state of technology development for the EDC concept has reached a level where a functionally self-contained ARS design centered around the advanced, liquid-cooled EDC is practical and desirable. The ARS design can also incorporate an S-CRS, an OGS, a CHCS, a NSS and water handling and coolant flow hardware. This entire system can be controlled and monitored by a single multi-purpose C/M I.

2. The EDC has been shown to be readily integrated with a B-CRS and OGS and can be successfully operated for periods in excess of 900 hours with minimum number of interfaces, using state-of-the-art hardware. No problems have been identified with using OGS generated H_2 in the EDC nor in using EDC exhaust gases in a B-CRS.

3. Closed-loop operation of an ASU serving as a spacecraft cabin environment simulator has demonstrated the capability of the unit to support long-duration testing of future EDCs and ARSs. The capability of the ASU to control process air temperature, dew point temperature, and pCO_2 within narrow bands has been demonstrated over a 900-hour endurance test.

4. An alternate anode current collector design, integral to the cell frame, is feasible and can be implemented with the advanced EDC cell hardware. The design uses a metal foil, metallurgically bonded to the current collector tabs. The new current collector design has shown significant reductions in internal IR losses and fabrication cost of the cell.

5. The optimum EDC current density required to minimize total equivalent weight of a spacecraft CO_2 removal subsystem is that current density that optimizes CO_2 removal efficiency. This is still true even when considering use of the electrical power generated by an EDC.

6. A series of supporting technology studies have verified that "B-level" performance goals for EDC technology advancement are achievable especially with respect to CO_2 removal efficiency. New EDC cell concepts and designs including a high moisture tolerance cell design, internal electrolyte reservoir cell design and an electrolyte mixture study have shown that cell voltages above 0.4 V can be achieved over fairly wide ranges of pCO_2, current density and RH. This level, however, is still approximately 0.1 V less than the goal established for the "B-level."

7. Mixed electrolytes investigated did not expand the EDC performance level beyond that demonstrated with the "B-level" configuration and concepts.

RECOMMENDATIONS

The following recommendations are a direct result of the program's conclusions:

1. A one-person capacity, experimental, laboratory breadboard ARS integrating the EDC with a CHCS, a S-CRS, an OGS, an NSS and water handling and distribution hardware has been designed, fabricated and assembled. A centralized C/M I approach for all ARS functions has been implemented. The next step recommended for advancing EDC technology as part of an ARS is to extensively test the integrated hardware. Emphasis should be placed on process control, process dynamics, "real world" variations in operating conditions and monitoring subsystem interactions. Testing of the subsystem hardware as an integrated system rather than on an individual basis should save development costs while simulating final end-item application.

2. Performance improvement experiments should be continued to more fully establish the new advanced "B-level" of EDC technology. The second phase of this effort should focus on (1) increasing cell voltage to greater than or equal to 0.5 V and (2) achieving constant performance over wide ranges in RH. The first phase of testing established that the new goal for CO_2 removal efficiency could be met. Following establishment of a new baseline EDC cell electrode/matrix/electrolyte combination through the "B-level" test activities, it should be incorporated and tested at a scaled-up level using the EDC hardware of the ARX-1 as a test bed.

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